
Heavy Dynamical Axions

UAM

Universidad Autónoma
de Madrid

in**visibles**Plus



Instituto de
Física
Teórica
UAM-CSIC

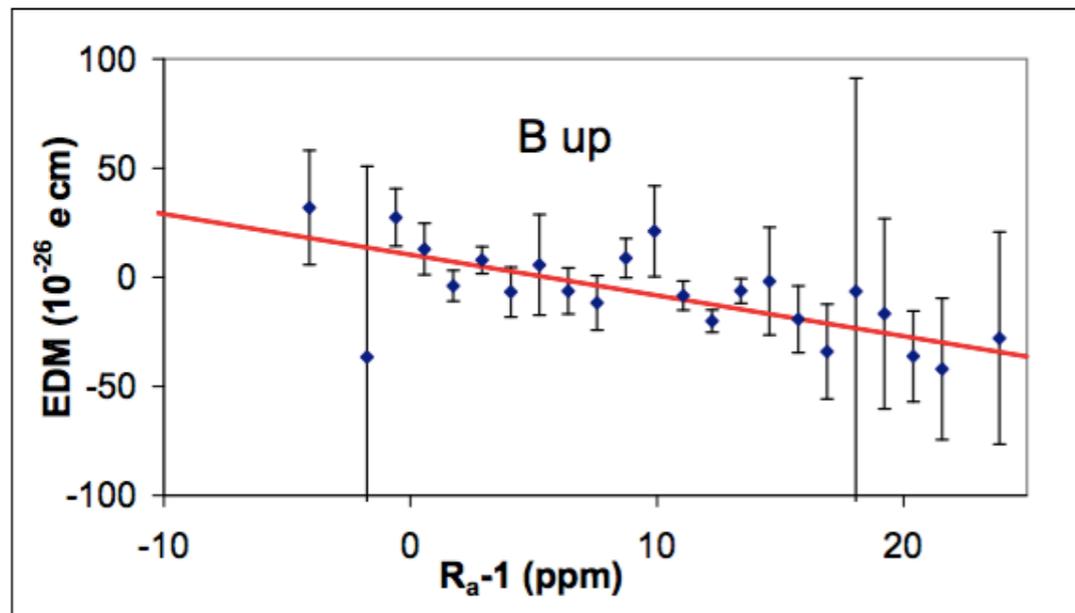
Rachel Houtz
Theory Seminar
Fermilab
September, 2019

In Collaboration with M. K. Gaillard (UC Berkeley), M. B. Gavela, R. del Rey, P. Quilez (IFT Madrid) [arXiv:1805.06465](https://arxiv.org/abs/1805.06465)

D. Croon (TRIUMF), V. Sanz (U. Sussex) [arXiv:1904.10967](https://arxiv.org/abs/1904.10967)

The strong CP problem and axions

$$\mathcal{L} = -\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu} + \frac{g^2\theta}{32\pi^2}G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \bar{q}Mq$$



C. A. Baker *et al*, hep-ex/0602020

- ❖ Dynamical solution employing $U(1)_{PQ}$ results in the axion

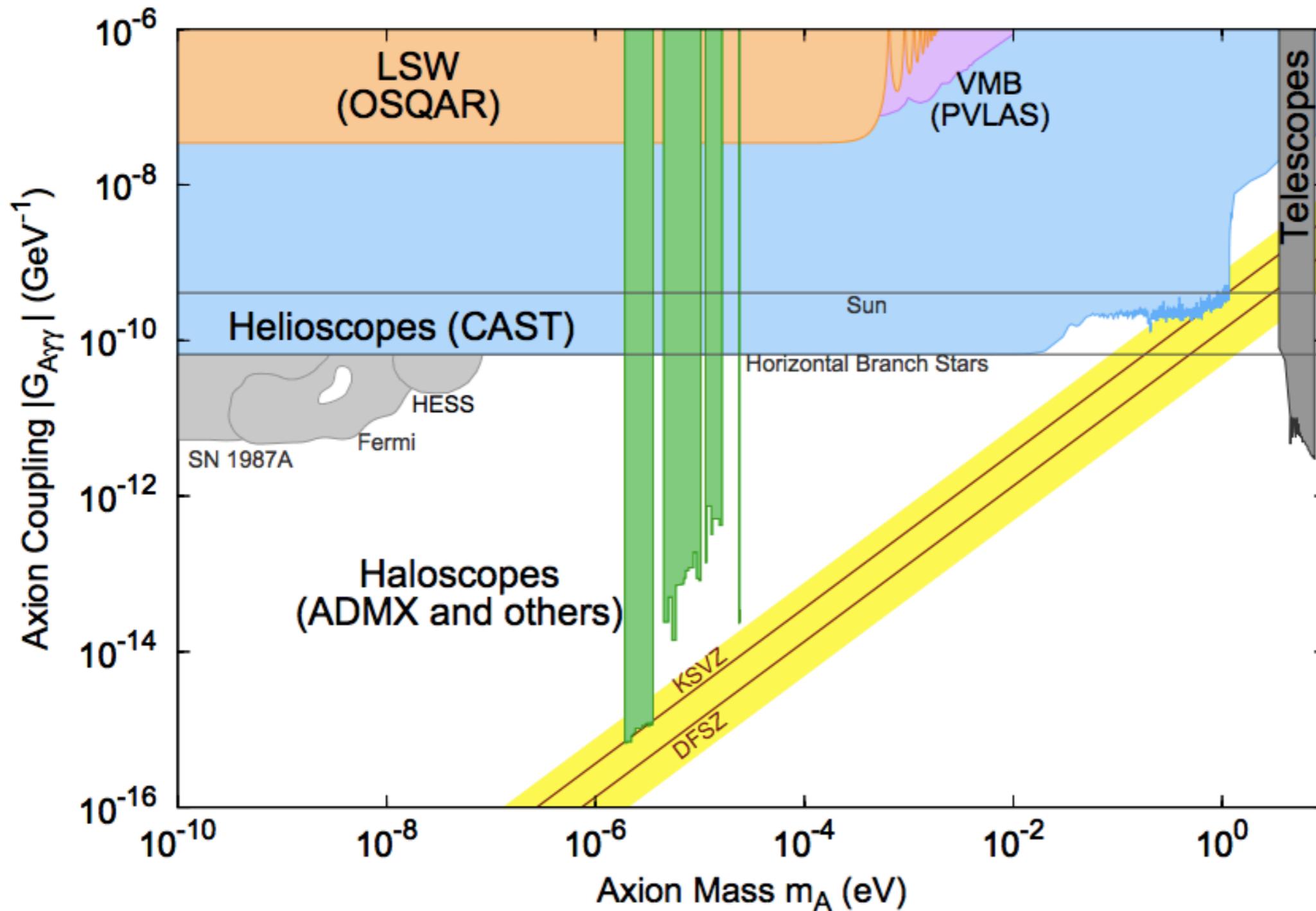
R. Peccei, H. Quinn (1977)

$$\mathcal{L} \ni \frac{g^2}{32\pi^2} \frac{a}{f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

F. Wilczek (1978) S. Weinberg (1978)

$$\bar{\theta} = \theta + \arg \det M \quad \bar{\theta} < 10^{-10}$$

Invisible axion parameter space

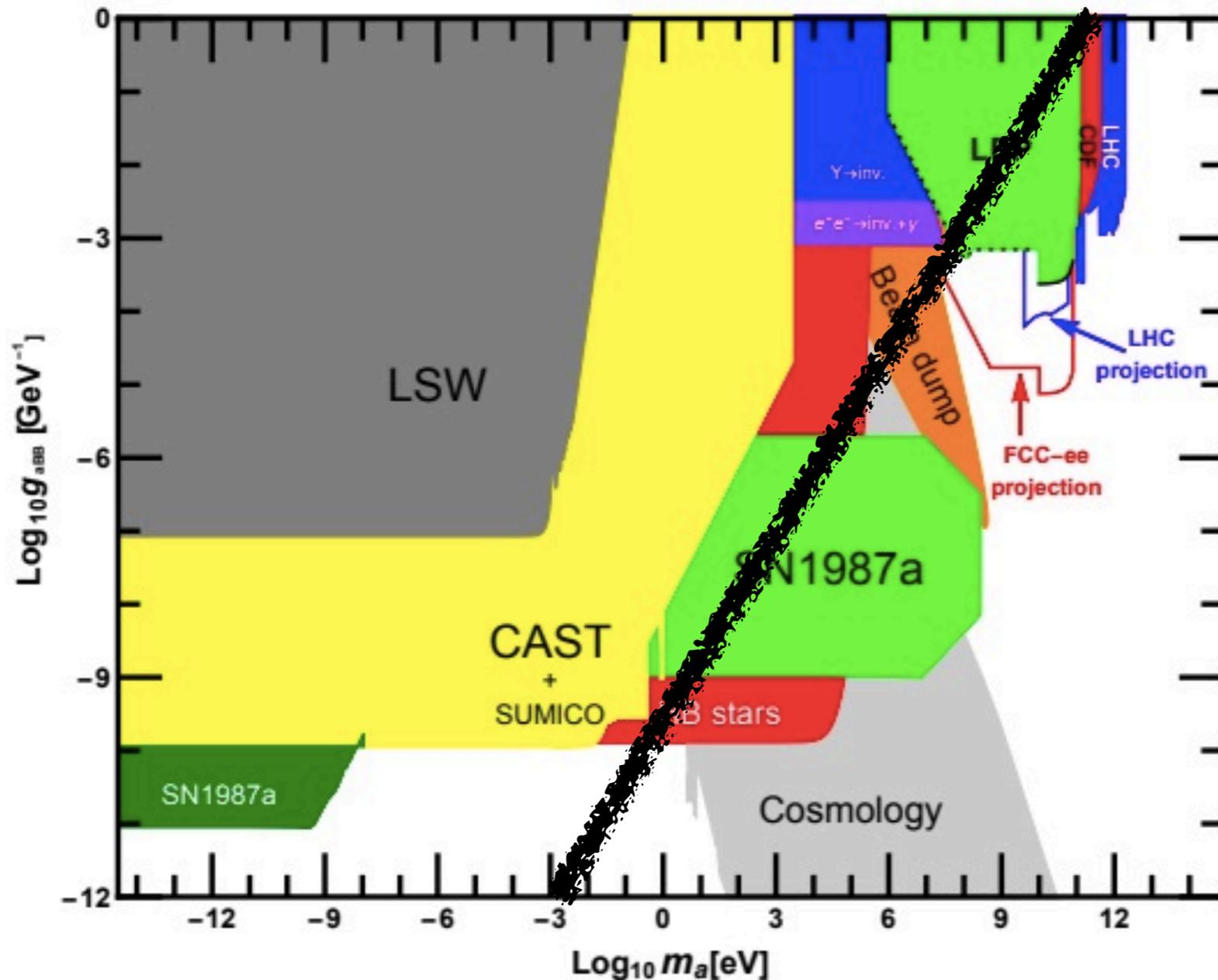


J. Kim (1979), M. Shifman, A. Vainshtein, V. Zakharov (1980)

M. Dine, W. Fischler, M. Srednicki (1981), Zhitnitsky (1980)

A. Ringwald, L. J. Rosenberg, G. Rybka, Particle Data Group (2018)

Invisible axion parameter space



 Extrapolation of the invisible axion expected region

J. Jaeckel, M. Spannowsky arXiv:1509.00476

I. Brivio, HEFT 2017

Strong CP problem and massless quarks

Under a chiral rotation:

$$\begin{aligned}\mathcal{L} &\ni -m_q \bar{q}q - \theta \frac{g^2}{32\pi^2} G\tilde{G} \\ &\rightarrow -m_q \bar{q}e^{2i\gamma_5\alpha}q - (\theta - 2\alpha) \frac{g^2}{32\pi^2} G\tilde{G}\end{aligned}$$

If $m_q = 0$, then this rotation is just a shift $\theta \rightarrow \theta - 2\alpha$

G. 't Hooft (1976)

- ➔ θ can be removed by field redefinition
- ➔ No longer physical
- ➔ Strong CP Problem solved

Motivation for exotic confining groups

(1) Additional color interactions can alter the m_a, f_a relationship

$$m_a^2 f_a^2 \approx m_\pi^2 f_\pi^2 \longrightarrow + \sim \Lambda_{\text{new}}^4$$

(2) Hide massless quark in bound states



$$\sim \Lambda_{\text{new}}$$

$$m_\psi = 0$$

K. Choi, JE Kim (1985)

A. Hook, arXiv:1411.3325

Dimopoulos, Susskind (1979)

Tye (1981) Rubakov (1997)

Berezhiani, Gianfagna, Giannotti, hep-ph/0009290

Fukuda, Harigaya, Ibe, Yanagida, arXiv:1504.06084

Gherghetta, Nagata, Shifman, arXiv:1604.01127

Dimopoulos, Hook, Huang, Marques-Tavares, arXiv:1606.03097

Agrawal, Howe, arXiv:1706:04195

J. Fuentes-Martin, M. Reig, A. Vicente, arXiv:1907.02550

Agrawal, Howe, 1712.05803

MK Gaillard, B. Gavela, RH, P. Quilez, R. del Rey, arXiv:1805.06465

B. Gavela, M. Ibe, P. Quilez, TT Yanagida, arXiv:1812.08174

Axicolor

- ❖ Add a massless quark and a new gauge group

$$\tilde{\Lambda} \gg \Lambda_{QCD}$$

Massless quark content

| | $SU(3)_{QCD}$ | $SU(\tilde{N})$ |
|--------|---------------|-----------------|
| ψ | □ | □ |

K. Choi, J. E. Kim (1985)

- ❖ When $SU(\tilde{N})$ confines, ψ forms bound states $\sim \tilde{\Lambda}$
- ❖ **Problem:** The new group has its own CP violating angle $\tilde{\theta}$
- ❖ **Solution:** Absorb $\tilde{\theta}$ with a new massless quark

Axicolor

- ❖ Add another massless quark χ charged under $SU(\tilde{N})$

- ❖ When $SU(\tilde{N})$ confines:

$$SU(4)_L \times SU(4)_R \rightarrow SU(4)_V$$

$$15 = 8 + 3 + \bar{3} + 1$$

This η' becomes the **dynamical axion**

- ❖ The decay constant is near the very high confinement scale
- ❖ This is then a UV completion for an invisible axion

Massless quark content

| | $SU(3)_{\text{QCD}}$ | $SU(\tilde{N})$ |
|--------|----------------------|-----------------|
| ψ | \square | \square |
| χ | $\underline{1}$ | \square |

Are there mass sources for all the axions?

1. Add an additional color group to contribute to axion mass

2. Introduce a new θ angle

3. Introduce a new axion

4. Get stuck with a light axion again

| | $SU(3)_{QCD}$ | $SU(N)_1$ | $SU(N)_2$ | ... |
|----------|---------------|-----------|-----------|-----|
| η | \square | \square | 1 | ... |
| χ_1 | 1 | \square | \square | ... |
| χ_2 | 1 | 1 | \square | ... |
| \vdots | \vdots | | | |

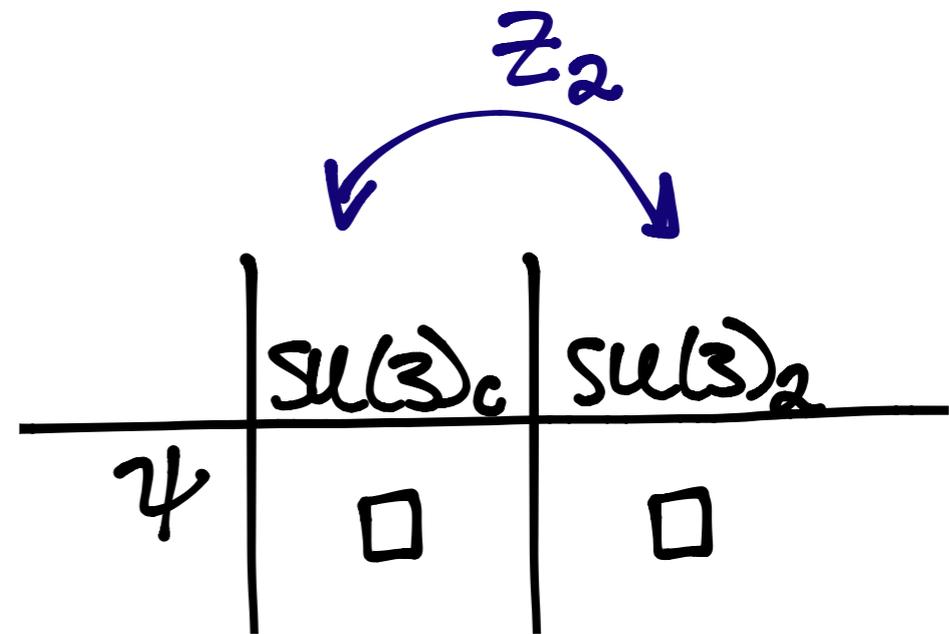
$$\mathcal{L}_{eff} \ni \Lambda_{QCD}^4 \cos\left(\frac{\eta'_{QCD}}{f_\pi} + \frac{a_1}{f_1}\right) + \Lambda_1^4 \cos\left(\frac{a_2}{f_2}\right) + \Lambda_2^4 \cos\left(\frac{a_3}{f_3}\right) + \dots$$

➔ You can avoid this problem if you relate two of the θ angles

➔ Otherwise, find additional mass sources for the axions

Massless quark and a Z_2

- ❖ Only one massless quark
- ❖ Complete Z_2 copy of the SM
- ❖ The $SU(3)_2$ θ -angle doesn't introduce new CP violating effects



A. Hook, arXiv:1411.3325

- ❖ Set up one Higgs VEV to be very large:

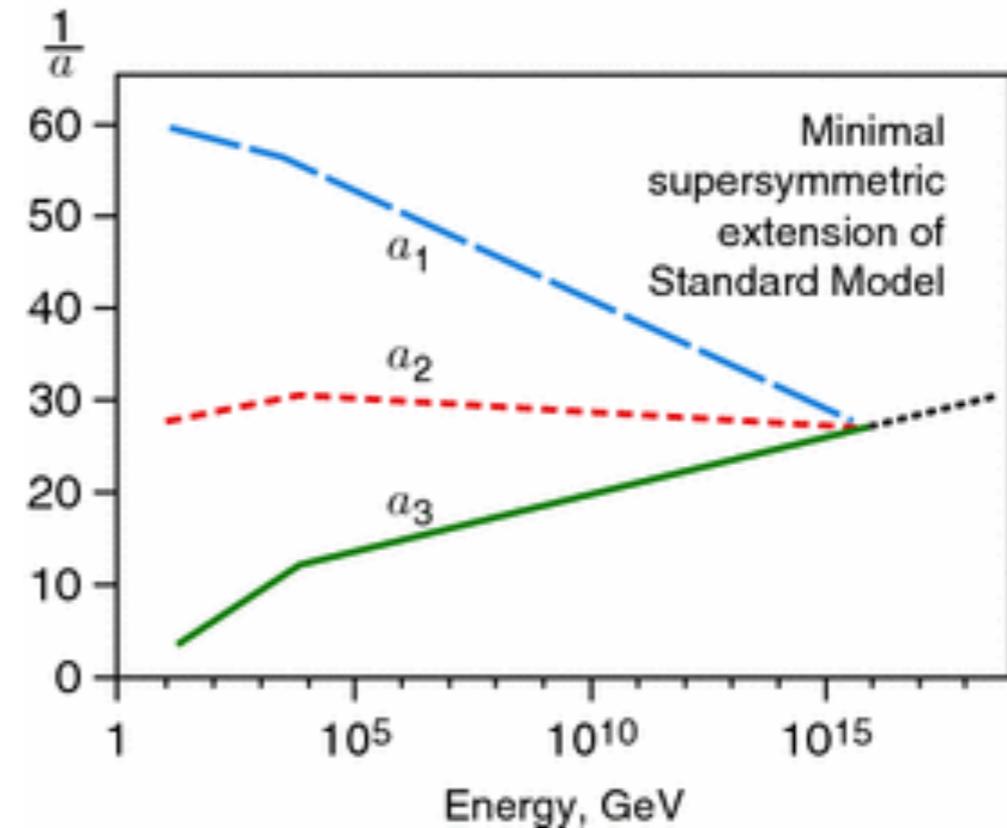
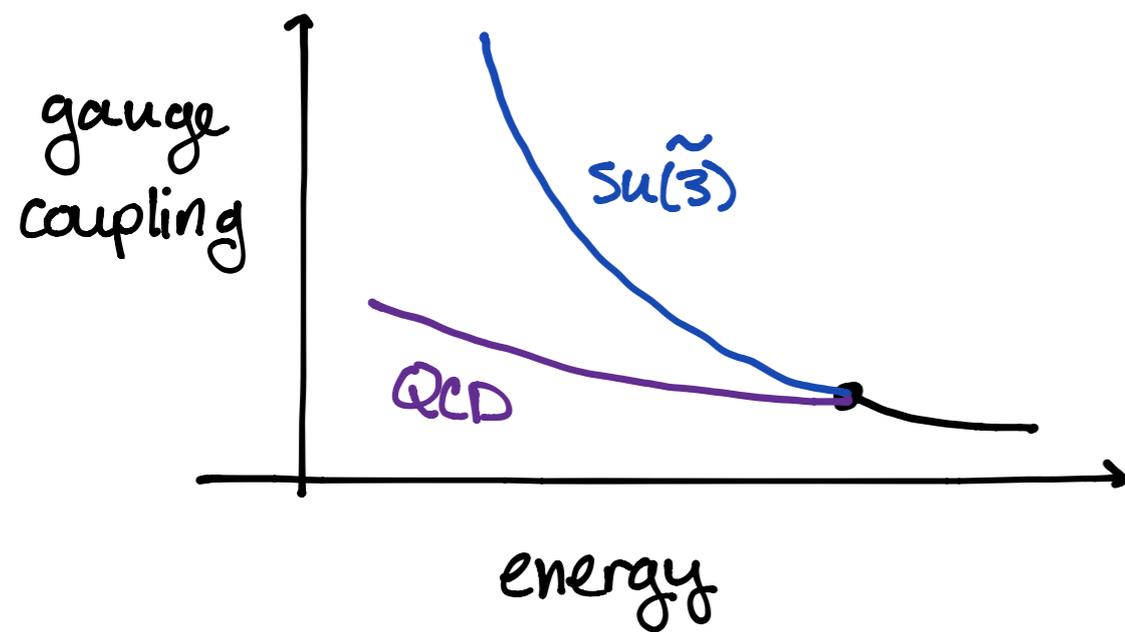
$$v_2 \gg v \quad \longrightarrow \quad m'_q \gg m_q \quad \longrightarrow \quad \Lambda'_{QCD} \gg \Lambda_{QCD}$$

➔ Bound states composed of massless quarks live at Λ'_{QCD}

Berezhiani, Gianfagna, Giannotti, hep-ph/0009290

Color unification

- ❖ Instead of a discrete symmetry, two color groups can be related by unification
- ❖ A single unified color sector with a single CP violating angle in the UV

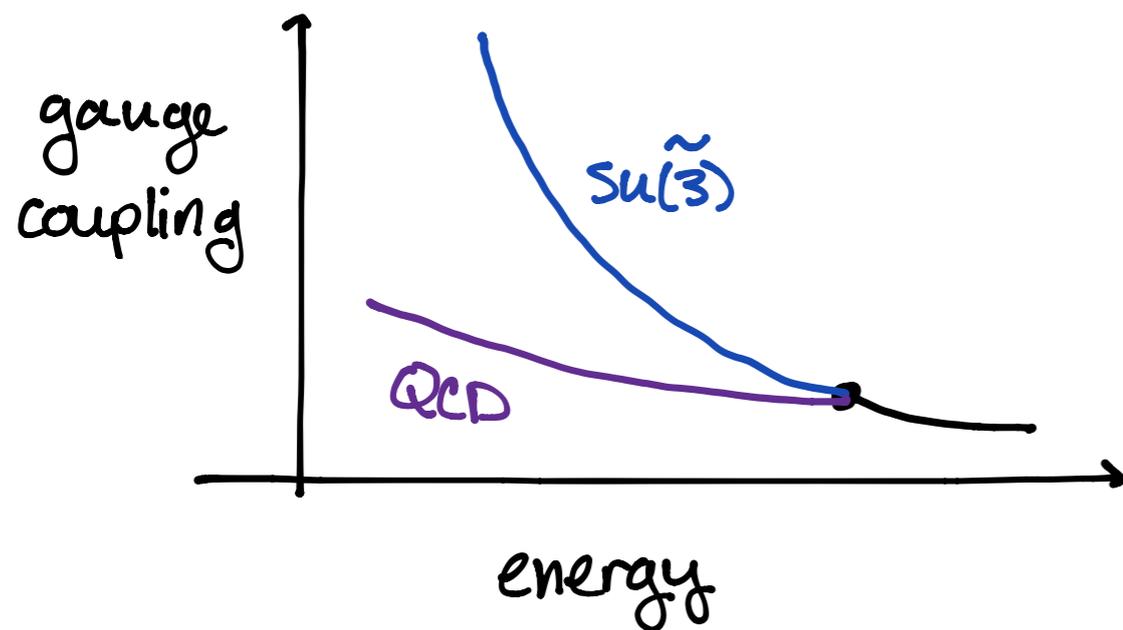


H. Georgi, S.L. Glashow (1974)
K. Sundermeyer (2014)

Gherghetta, Nagata, Shifman, arXiv:1604.01127
V.A. Rubakov, hep-ph/9703409

Color unified dynamical axion

- ❖ Introduce massless quark $m_\Psi = 0$ M.K. Gaillard, M.B. Gavela, R.H., P. Quilez, R. Del Rey, arXiv:1805.06465
- ❖ QCD lives inside a larger unified color group, which breaks to QCD and $SU(\tilde{3})$ at some high unification scale
- ❖ The new color group to allows Ψ to form bound states near its confinement $\sim \text{TeV}$



- ❖ A bound state will be a dynamical axion, with its own m_a, f_a relationship

Massless quark and unification

- ❖ The massless quark to absorb the unified group's θ_6

| | $SU(6)$ | $SU(2)_L$ | $U(1)_Y$ |
|----------|---------|-----------|----------|
| Ψ_L | 20 | 1 | 0 |

$$SU(6) \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_{\text{QCD}} \times SU(\tilde{3}) \times U(1)$$

- ❖ Below unification scale:

$$\begin{aligned} \Psi(20) \rightarrow & (1, 1)(-3) + (1, 1)(+3) \\ & + (3, \bar{3})(-1) + (\bar{3}, 3)(+1) \end{aligned}$$

| | $SU(3)_{\text{QCD}}$ | $SU(\tilde{3})$ |
|----------------|----------------------|-----------------|
| ψ_L | \square | $\bar{\square}$ |
| $(\psi^c)_L$ | $\bar{\square}$ | \square |
| ψ_{ν_1} | 1 | 1 |
| ψ_{ν_2} | 1 | 1 |

The SM fermions

We embed the SM quarks in
□ representations of SU(6):

$$Q_L^{(6)} \equiv (q, \tilde{q})_L$$

$$U_R^{(6)} \equiv (u, \tilde{u})_R$$

$$D_R^{(6)} \equiv (d, \tilde{d})_R$$

&

The SU(6) partner fields
need to be decoupled

$$m_{\tilde{q}} > m_q$$

$$m_{\tilde{u}} > m_u$$

$$m_{\tilde{d}} > m_d$$

1. Equal mass partners are phenomenologically forbidden
2. The partner fields need to decouple in order to separate the running of $SU(3)_c$ and $SU(\tilde{3})$

Removing the unification partners

Makes things difficult


$$Q_L^{(6)} \equiv (q, \tilde{q})_L$$

- ❖ Any scalar that gives $\tilde{q}, \tilde{u}, \tilde{d}$ a mass would have to be an $SU(2)_L$ doublet with a high VEV, affecting the W and Z boson masses

$$\tilde{v} \gg v$$

- ❖ Leaving the quarks massless and in the theory when $SU(\tilde{3})$ confines would trigger EWSB at the confinement scale

$$\tilde{\Lambda} \gg v$$

➡ This requires more model building

Matter content above and below CUT breaking

$$SU(6) \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_{\text{QCD}} \times SU(\tilde{3})$$

| | $SU(6)$ | $SU(2)_L$ | | $SU(3)$ | $SU(\tilde{3})$ | $SU(2)_L$ | | |
|-------------|-----------------|--------------|--------------------------------------|-----------------|-----------------|-----------------|---|--------------|
| Q_L | \square | \square | $\xrightarrow{\Lambda_{\text{CUT}}}$ | \square | $\mathbb{1}$ | \square | } Goal: provide a mechanism for these fields to form mass terms | |
| \bar{U}_R | $\bar{\square}$ | $\mathbb{1}$ | | $\bar{\square}$ | $\mathbb{1}$ | $\mathbb{1}$ | | |
| \bar{D}_R | $\bar{\square}$ | $\mathbb{1}$ | | $\bar{\square}$ | $\mathbb{1}$ | $\mathbb{1}$ | | |
| Ψ | 20 | $\mathbb{1}$ | | $\mathbb{1}$ | \square | \square | | |
| | | | | \tilde{q}_L | $\mathbb{1}$ | \square | | \square |
| | | | | \tilde{u}_R | $\mathbb{1}$ | $\bar{\square}$ | | $\mathbb{1}$ |
| | | | | \tilde{d}_R | $\mathbb{1}$ | $\bar{\square}$ | | $\mathbb{1}$ |
| | | | | 4 | \square | $\bar{\square}$ | | $\mathbb{1}$ |
| | | | | 24_{ν} | $\mathbb{1}$ | $\mathbb{1}$ | | $\mathbb{1}$ |

The prime sector

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(3)_{\text{diag}}$$

| | $SU(6)$ | $SU(3')$ | $SU(2)_L$ |
|--------------|-----------------|-----------------|--------------|
| Q_L | \square | $\mathbb{1}$ | \square |
| \bar{U}_R | $\bar{\square}$ | $\mathbb{1}$ | $\mathbb{1}$ |
| \bar{D}_R | $\bar{\square}$ | $\mathbb{1}$ | $\mathbb{1}$ |
| \bar{q}'_R | $\mathbb{1}$ | $\bar{\square}$ | \square |
| u'_L | $\mathbb{1}$ | \square | $\mathbb{1}$ |
| d'_L | $\mathbb{1}$ | \square | $\mathbb{1}$ |
| Ψ | 20 | $\mathbb{1}$ | $\mathbb{1}$ |
| Δ | \square | $\bar{\square}$ | $\mathbb{1}$ |

❖ We can form terms like:

$$\bar{q}'_R \Delta^* Q_L$$

} These fields pair up with the tilde fields to form masses

← Scalar field responsible for CUT breaking

Decoupling the $SU(6)$ Partner Fields

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(3)_{\text{diag}}$$

$$\mathcal{L} \ni \Lambda_{\text{CUT}} \left(\kappa_q \overline{q'_R} \tilde{q}_L + \kappa_u u'_L \overline{\tilde{u}_R} + \kappa_d d'_L \overline{\tilde{d}_R} \right) + \text{h.c.}$$

- ❖ Note that $SU(2)_L$ remains unbroken in this scheme
- ❖ For now, we take all the κ 's to be $O(1)$

- ❖ The prime and tilde quarks have masses around the CUT scale:
 $\Lambda_{\text{CUT}} \approx m_{\tilde{q}} \gg m_q$
 $\Lambda_{\text{CUT}} \approx m_{\tilde{u}} \gg m_u$
 $\Lambda_{\text{CUT}} \approx m_{\tilde{d}} \gg m_d$

$$SU(6) \times SU(3)' \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(3)_{\text{diag}}$$

Prime sector

| | $SU(6)$ | $SU(3)'$ | $SU(2)_L$ |
|--------------|-----------------|-----------------|--------------|
| Q_L | \square | $\mathbb{1}$ | \square |
| \bar{U}_R | $\bar{\square}$ | $\mathbb{1}$ | $\mathbb{1}$ |
| \bar{D}_R | $\bar{\square}$ | $\mathbb{1}$ | $\mathbb{1}$ |
| \bar{q}'_R | $\mathbb{1}$ | $\bar{\square}$ | \square |
| u'_L | $\mathbb{1}$ | \square | $\mathbb{1}$ |
| d'_L | $\mathbb{1}$ | \square | $\mathbb{1}$ |
| Ψ | 20 | $\mathbb{1}$ | $\mathbb{1}$ |
| Δ | \square | $\bar{\square}$ | $\mathbb{1}$ |

Λ_{CUT}

| | $SU(3)$ | $SU(3)_{\text{diag}}$ | $SU(2)_L$ |
|----------------|-----------------|-----------------------|--------------|
| q_L | \square | $\mathbb{1}$ | \square |
| \bar{u}_R | $\bar{\square}$ | $\mathbb{1}$ | $\mathbb{1}$ |
| \bar{d}_R | $\bar{\square}$ | $\mathbb{1}$ | $\mathbb{1}$ |
| q | \square | $\bar{\square}$ | $\mathbb{1}$ |
| $2q_v$ | $\mathbb{1}$ | $\mathbb{1}$ | $\mathbb{1}$ |
| \tilde{q}'_L | $\mathbb{1}$ | \square | \square |
| \tilde{u}'_R | $\mathbb{1}$ | $\bar{\square}$ | $\mathbb{1}$ |
| \tilde{d}'_R | $\mathbb{1}$ | $\bar{\square}$ | $\mathbb{1}$ |
| \bar{q}'_R | $\mathbb{1}$ | $\bar{\square}$ | \square |
| u'_L | $\mathbb{1}$ | \square | $\mathbb{1}$ |
| d'_L | $\mathbb{1}$ | \square | $\mathbb{1}$ |

Massless quark sector

Obtain mass near the CUT breaking scale

QCD Strong CP Problem Solved!*

*almost

The θ' Issue

$$\mathcal{L} \ni \theta_6 \frac{\alpha_6}{8\pi} G_6 \tilde{G}_6 + \theta' \frac{\alpha'}{8\pi} G' \tilde{G}'$$



$$\mathcal{L} \ni (\theta_6 + \theta') \frac{\alpha_{\text{diag}}}{8\pi} G_{\text{diag}} \tilde{G}_{\text{diag}} + \theta_6 \frac{\alpha_c}{8\pi} G_c \tilde{G}_c$$

- ❖ The θ' can contaminate the visible sector via Δ
- ❖ θ' must be removed \rightarrow This requires more model building
- ❖ Note that this comes from the problem of decoupling unification partners

Massless Fermion Charged Under $SU(3)'$

| | $SU(6)$ | $SU(3)'$ | $SU(2)_L$ | | | $SU(3)$ | $SU(3)_{diag}$ | $SU(2)_L$ |
|--------|---------|-----------|-----------|-------------------------------|-----------------|-----------|-----------------|-----------|
| Ψ | 20 | 1 | 1 | $\xrightarrow{\Lambda_{CUT}}$ | 4 | \square | $\bar{\square}$ | 1 |
| χ | 1 | \square | 1 | | χ | 1 | \square | 1 |
| | | | | | 24 _v | 1 | 1 | 1 |

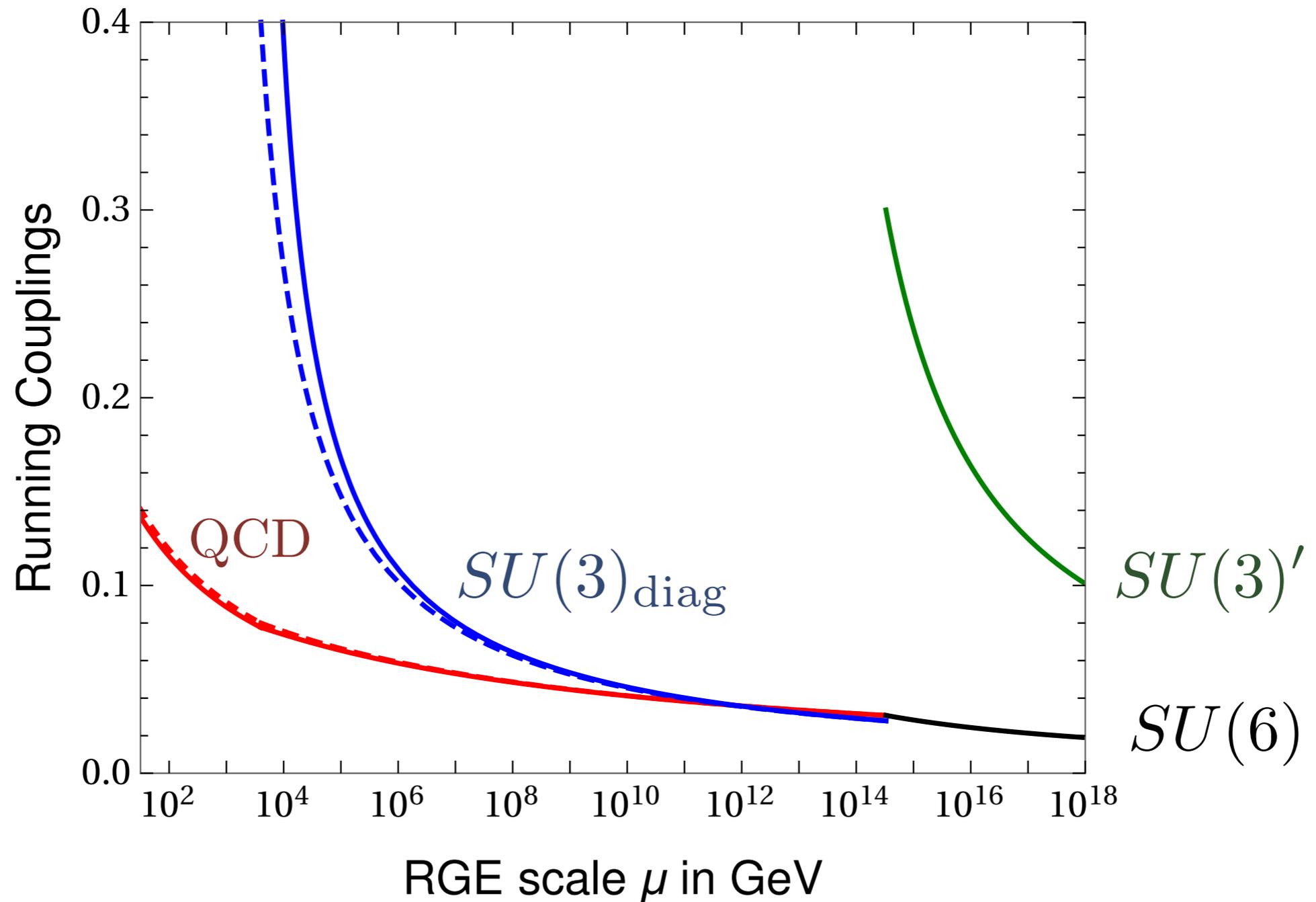

 The new massless quark

- ❖ Goal: $SU(3)_{diag}$ confines at a higher scale than $SU(3)_c$

$$\frac{1}{\alpha_{diag}(\mu)} = \frac{1}{\alpha_6(\mu)} + \frac{1}{\alpha'(\mu)} \quad \mu = \Lambda_{CUT}$$

$$\alpha_c(\Lambda_{CUT}) = \alpha_6(\Lambda_{CUT})$$

Unification and confinement

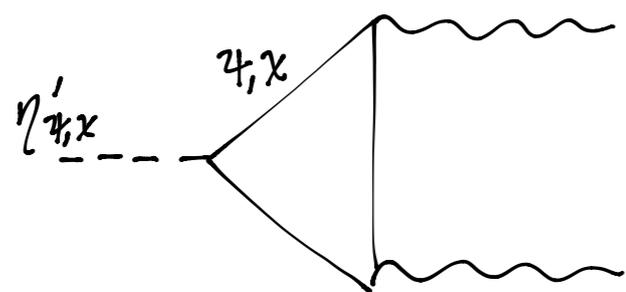


$SU(3)_{\text{diag}}$ confinement

- ❖ Chiral symmetry breaking: $U(4)_L \times U(4)_R \rightarrow U(4)_V$
- ❖ This results in 16 pGB's: $16 = 8_c + \bar{3}_c + 3_c + 1_c + 1_c$

- ❖ The “pion” masses:  $\sim \Lambda_{\text{diag}}^4$

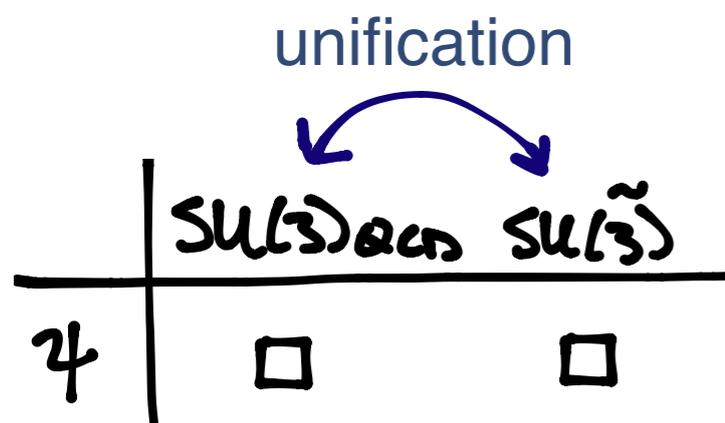
- ❖ The η' masses:



$$\mathcal{L}_{eff} = \Lambda_{\text{diag}}^4 \cos\left(\frac{2\eta'_{\chi}}{f_d} + \sqrt{6}\frac{\eta'_{\psi}}{f_d}\right) + \Lambda_{\text{QCD}}^4 \cos\left(\frac{2\eta'_{\text{QCD}}}{f_{\pi}} + \sqrt{6}\frac{\eta'_{\psi}}{f_d}\right)$$

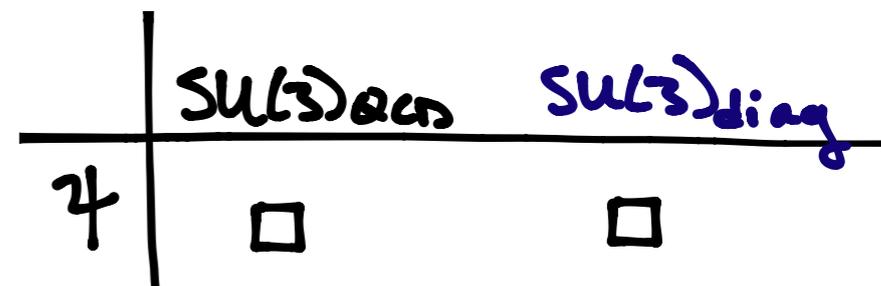
→ This looks like **2** masses for **3** η' pseudoscalars

Check-in



- ❖ Started with a simple picture far below Λ_{CUT}

- ❖ Removing the unification partners forced us to introduce another non-Abelian gauge group



Check-in

unification



| | $SU(3)_{\text{em}}$ | $SU(3)$ |
|--------|---------------------|-----------|
| ψ | \square | \square |

- ❖ Started with a simple picture far below Λ_{CUT}

- ❖ Removing the unification partners forced us to introduce another non-Abelian gauge group

| | $SU(3)_{\text{em}}$ | $SU(3)_{\text{diag}}$ |
|--------|---------------------|-----------------------|
| ψ | \square | \square |
| χ | $\underline{1}$ | \square |

- ❖ Introduce a new massless quark
- ❖ Got stuck with a light axion again
 1. Start looking into different unification schemes
 2. Look for additional mass sources for the axions

Small size instantons and axion mass

- ❖ Typically, at high scales α_{QCD} is very small
- ❖ If new physics alters RG flow, large couplings can induce new instanton corrections to the axion mass

J. Flynn, L. Randall (1987)

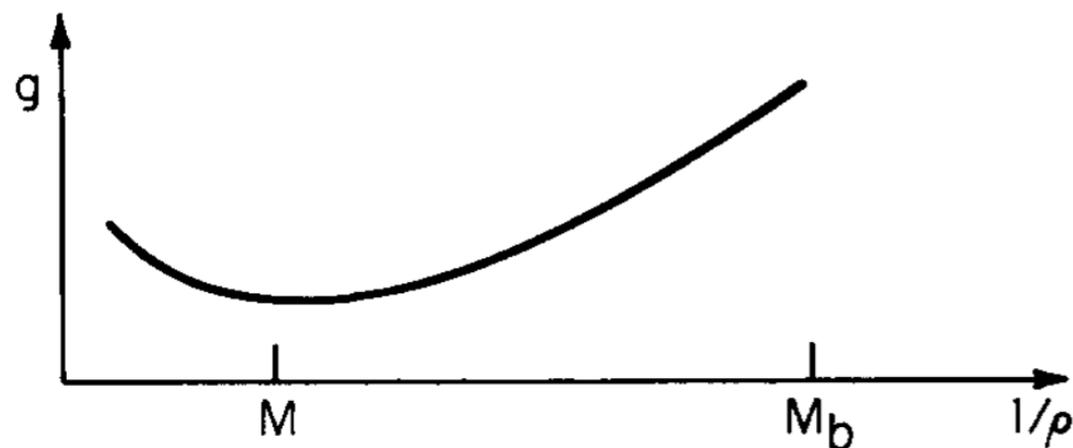


Fig. 1. Coupling g as a function of $1/\rho$.

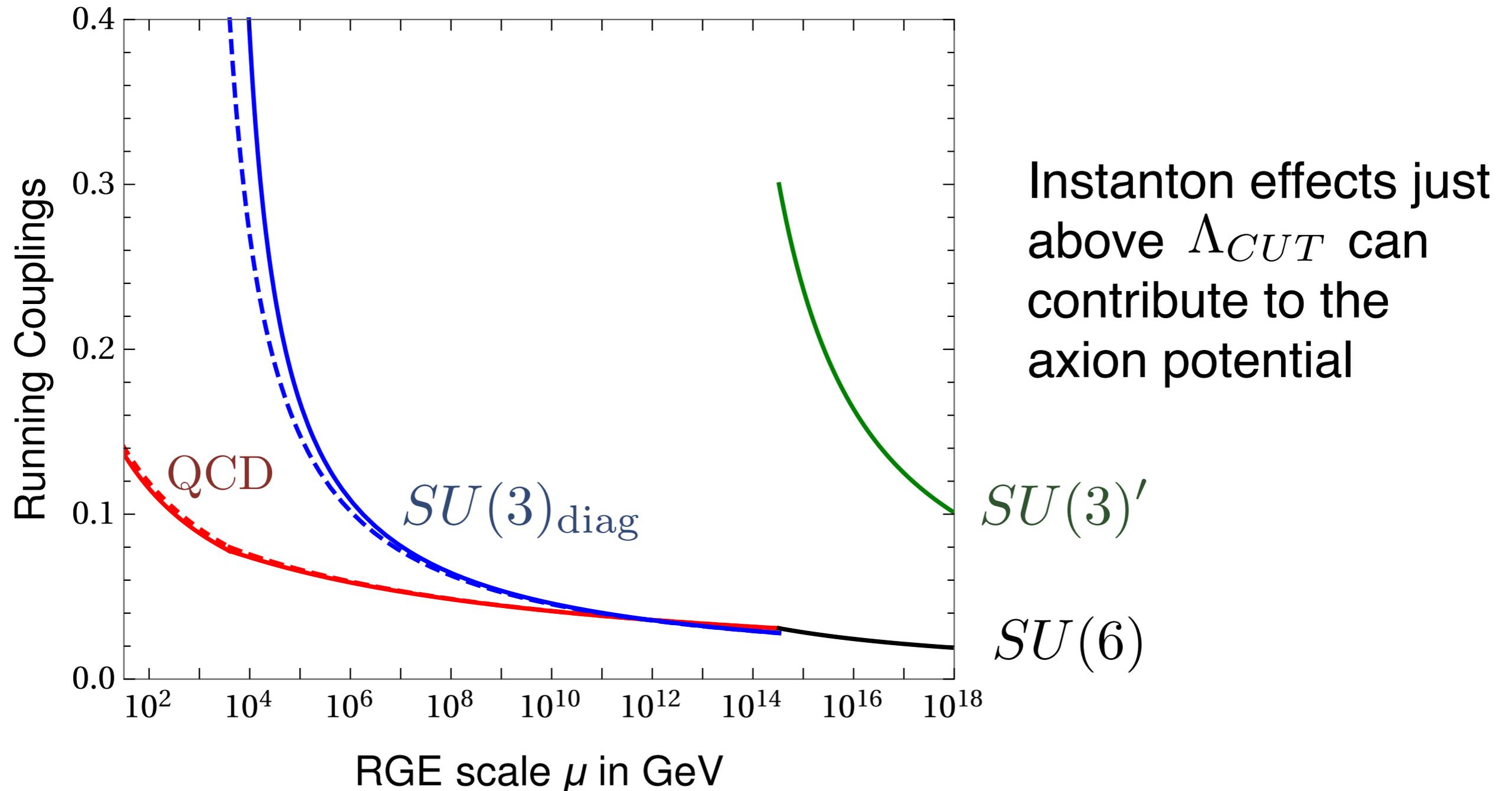
P. Agrawal, K. Howe arXiv:1710.04213

$$SU(3) \times \dots \times SU(3) \rightarrow SU(3)_c$$
$$\frac{1}{\alpha_{\text{QCD}}(\mu)} = \frac{1}{\alpha_1(\mu)} + \frac{1}{\alpha_2(\mu)} + \dots + \frac{1}{\alpha_N(\mu)}$$
$$\mu = M_b$$

M. Dine, N. Seiberg (1986)

B. Holdom, M. Peskin (1982)

Small size instanton effects



Small Size Instantons - calculating their effects

Dilute Instanton gas
without fermions:

$$\Lambda_{SSI}^4 = \int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)]$$

Instanton density:

$$D[\alpha'(1/\rho)] = C_{inst} \left(\frac{2\pi}{\alpha'(1/\rho)} \right)^6 e^{-\frac{2\pi}{\alpha'(1/\rho)}} e^{-4\pi^2 \rho \mathcal{V}^2}$$

❖ Where Λ_{SSI} is the small-size instanton contribution to the axion potential G. 't Hooft (1976) Callan, Dashen, Gross, (1978)

❖ For benchmark $\alpha'(\Lambda_{CUT}) = .3$:

$$\Lambda_{SSI}^4 = 3.0 \times 10^{-5} \Lambda_{CUT}^4, \quad \Lambda_{CUT} \sim 10^{15} \text{ GeV}$$

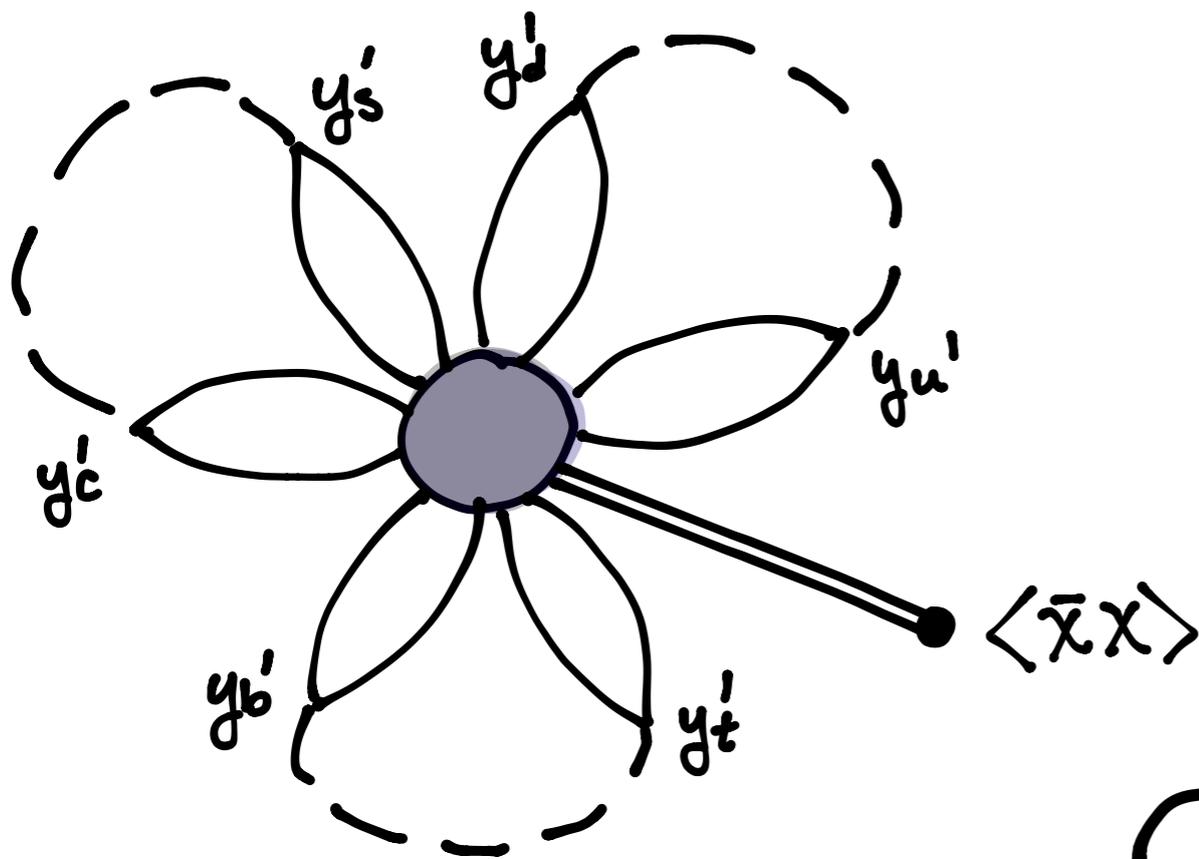
Small size instantons with fermions

- ❖ Adding fermion effects gives an instanton suppression

M. A. Shifman, A. I. Vainshtein, V. I. Zakharov (1980)

J. Flynn, L. Randall (1987)

Callan, Dashen, Gross, (1978)



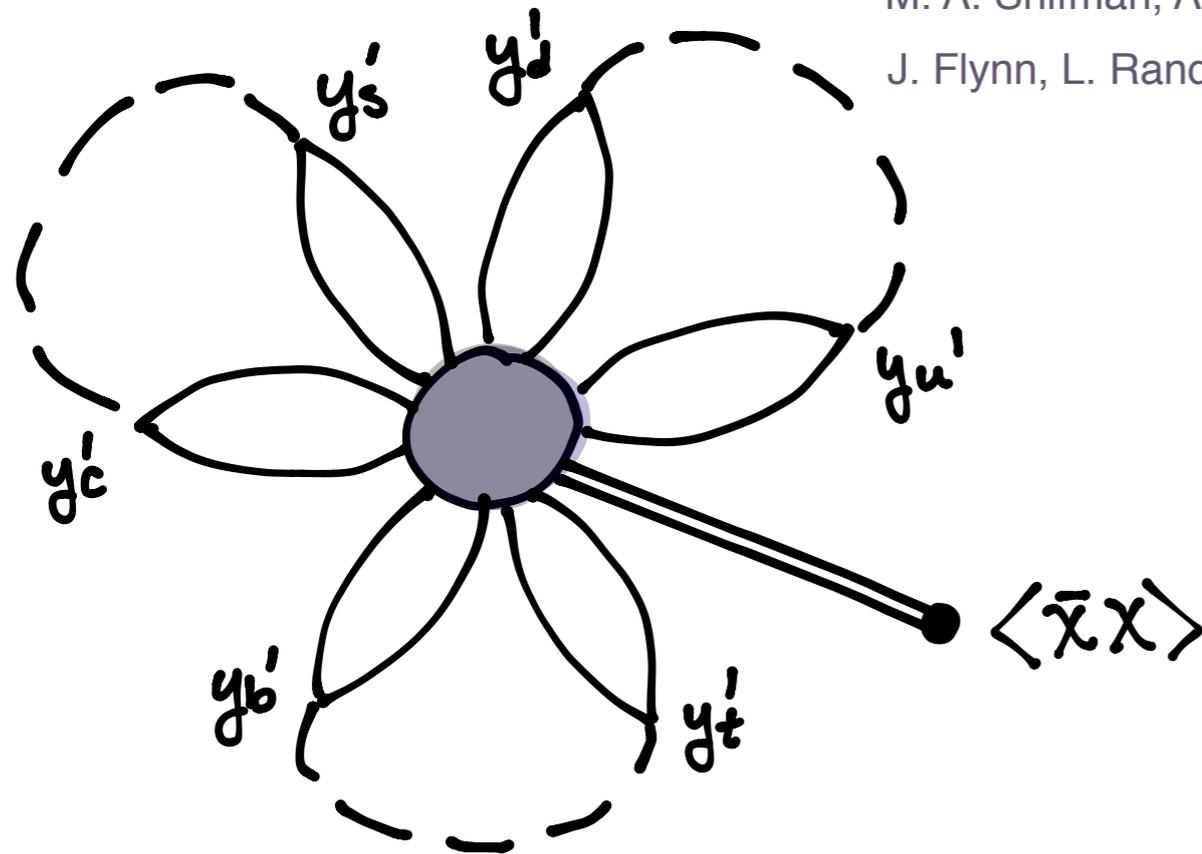
Fermion suppression factor

$$\Lambda_{SSI}^4 = \int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \left(\frac{2}{3} \pi^2 \rho^3 \langle \bar{\chi} \chi \rangle \right) \frac{1}{(4\pi)^6} \prod_i y'_u{}^i y'_d{}^i$$

Small size instantons effects

M. A. Shifman, A. I. Vainshtein, V. I. Zakharov (1980)

J. Flynn, L. Randall (1987) Callan, Dashen, Gross, (1978)

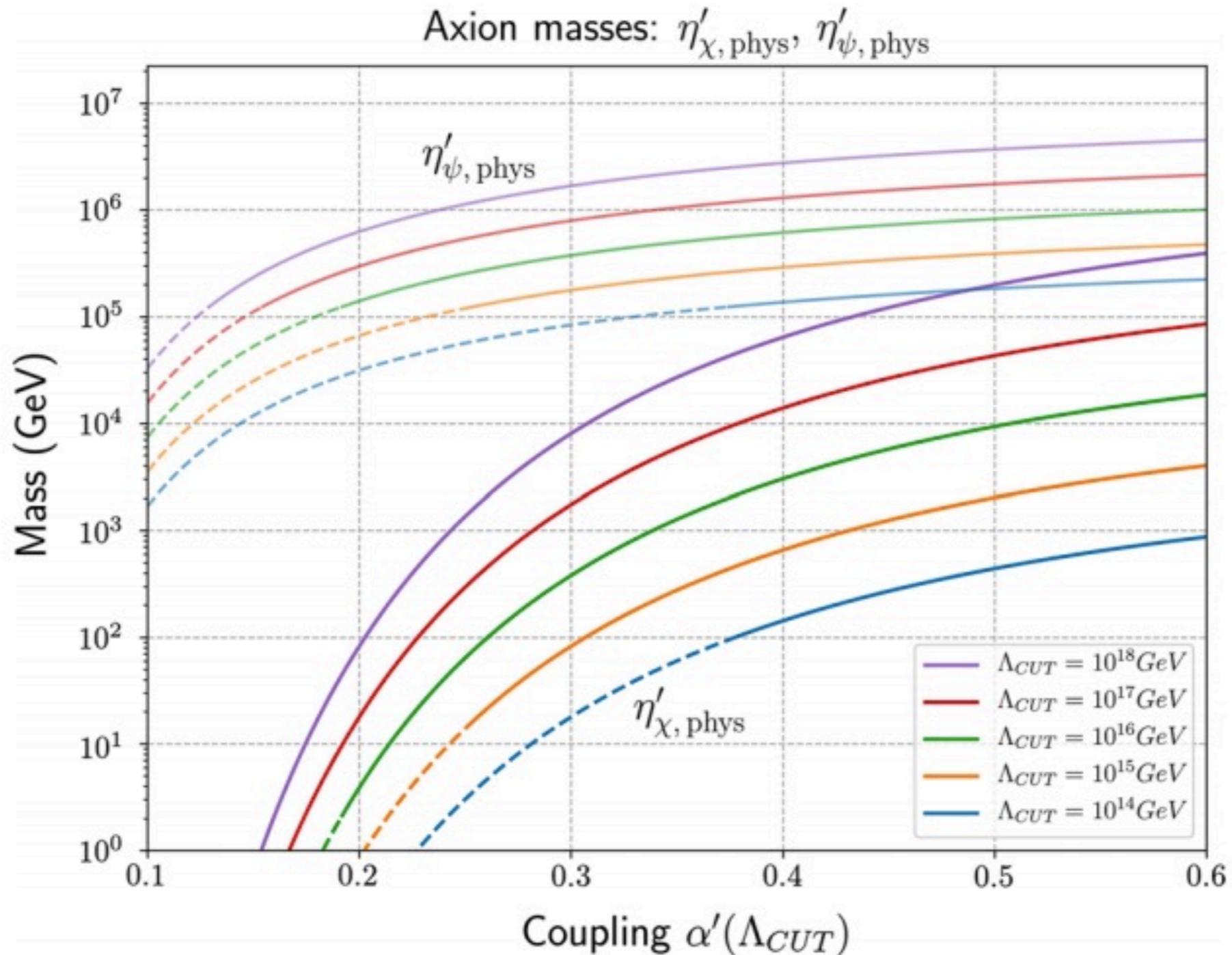


- ❖ This interaction induces a scale in the axion potential

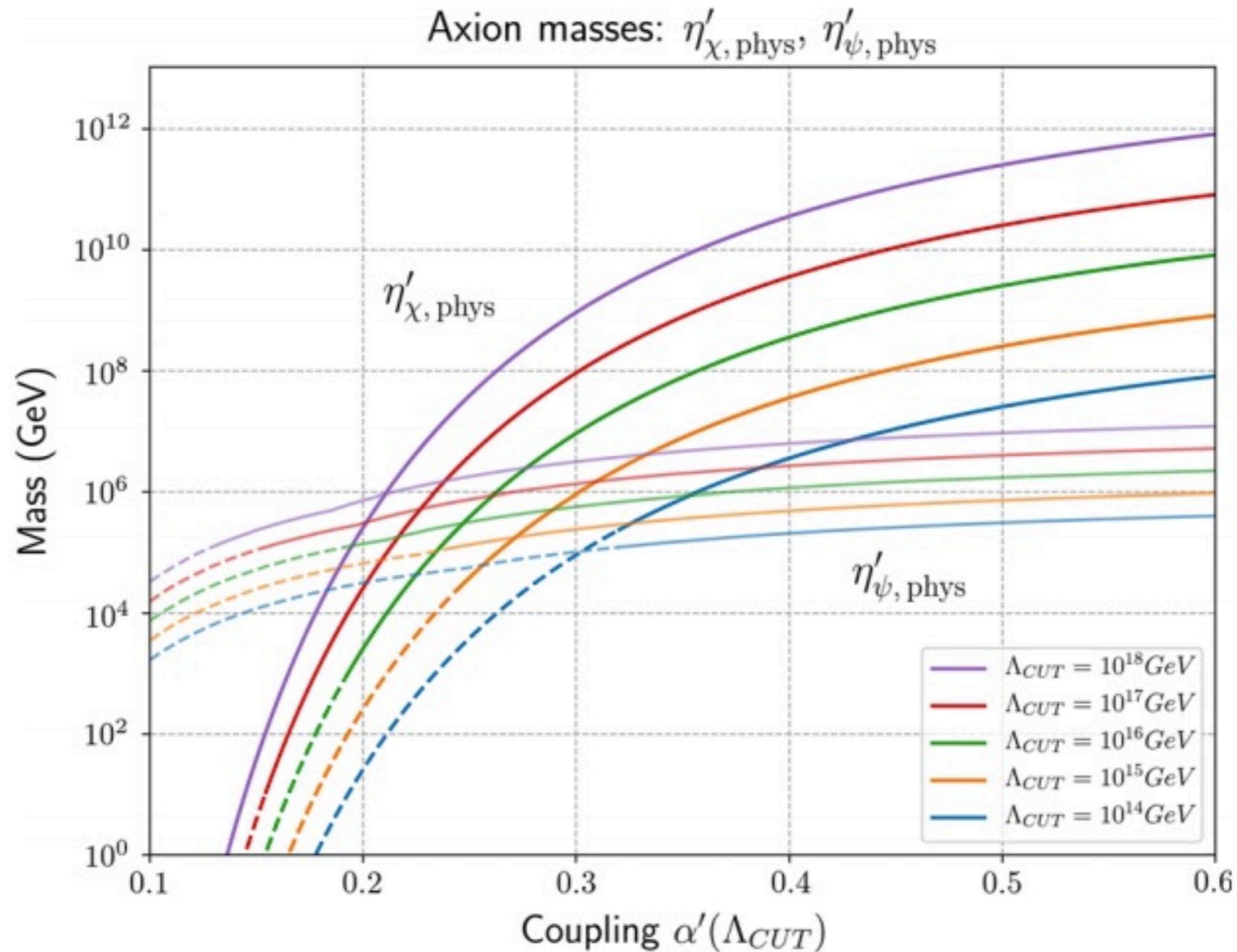
Typical contributions from Λ_{diag} confinement

$$\mathcal{L}_{eff} = \Lambda_{SSI}^4 \cos\left(2\frac{\eta'_\chi}{f_d}\right) + \Lambda_{\text{diag}}^4 \cos\left(2\frac{\eta'_\chi}{f_d} + \sqrt{6}\frac{\eta'_\psi}{f_d}\right) + \Lambda_{\text{QCD}}^4 \cos\left(\sqrt{6}\frac{\eta'_\psi}{f_d}\right)$$

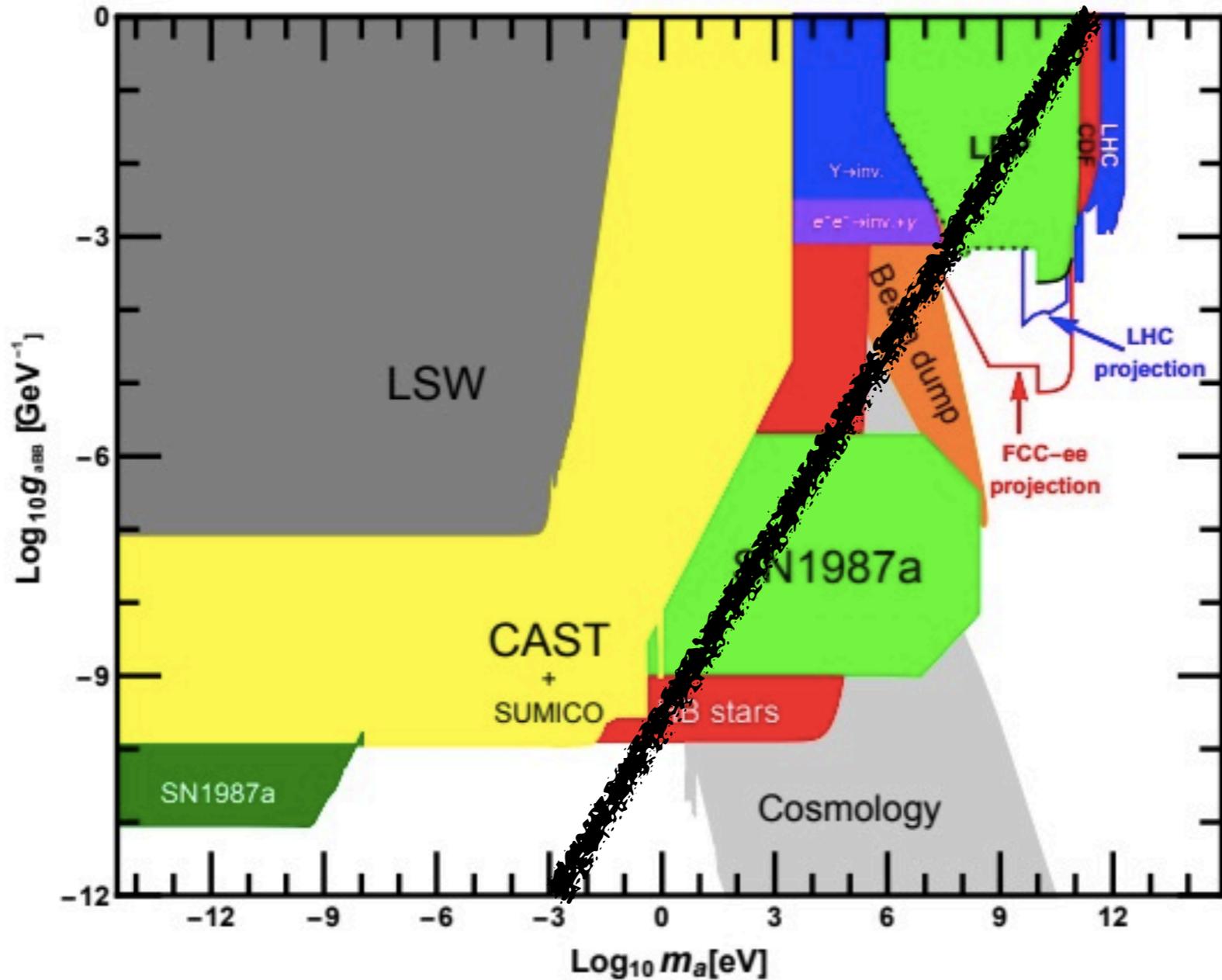
$O(0.1)$ prime Yukawa couplings



$O(1)$ prime Yukawa couplings



Very heavy axions



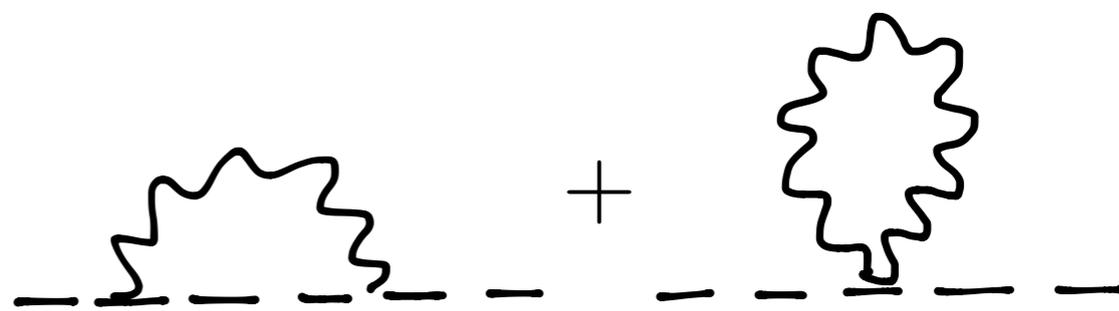
— Extrapolation of the invisible axion expected region

J. Jaeckel, M. Spannowsky arXiv:1509.00476

I. Brivio, HEFT 2017

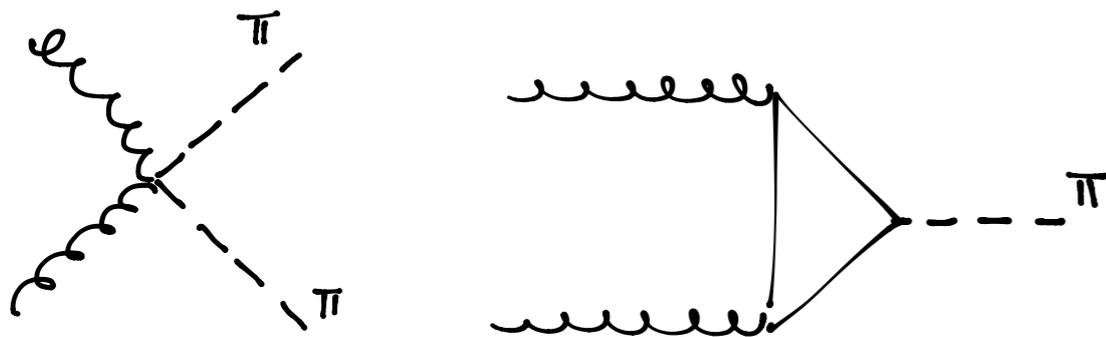
Low Energy Spectrum

- ❖ The SM η'_{QCD} and the rest of the SM spectrum below Λ_{diag}
- ❖ In most of the parameter space, the axions are too heavy to produce at colliders
- ❖ Exotic QCD colored “pions”
 - ❖ Color octets
 - ❖ Color triplets
- ❖ Sterile neutrinos ψ_ν , suppressed by Λ_{CUT} , basically invisible



Collider phenomenology

- ❖ Collider accessible states are QCD colored “pions”

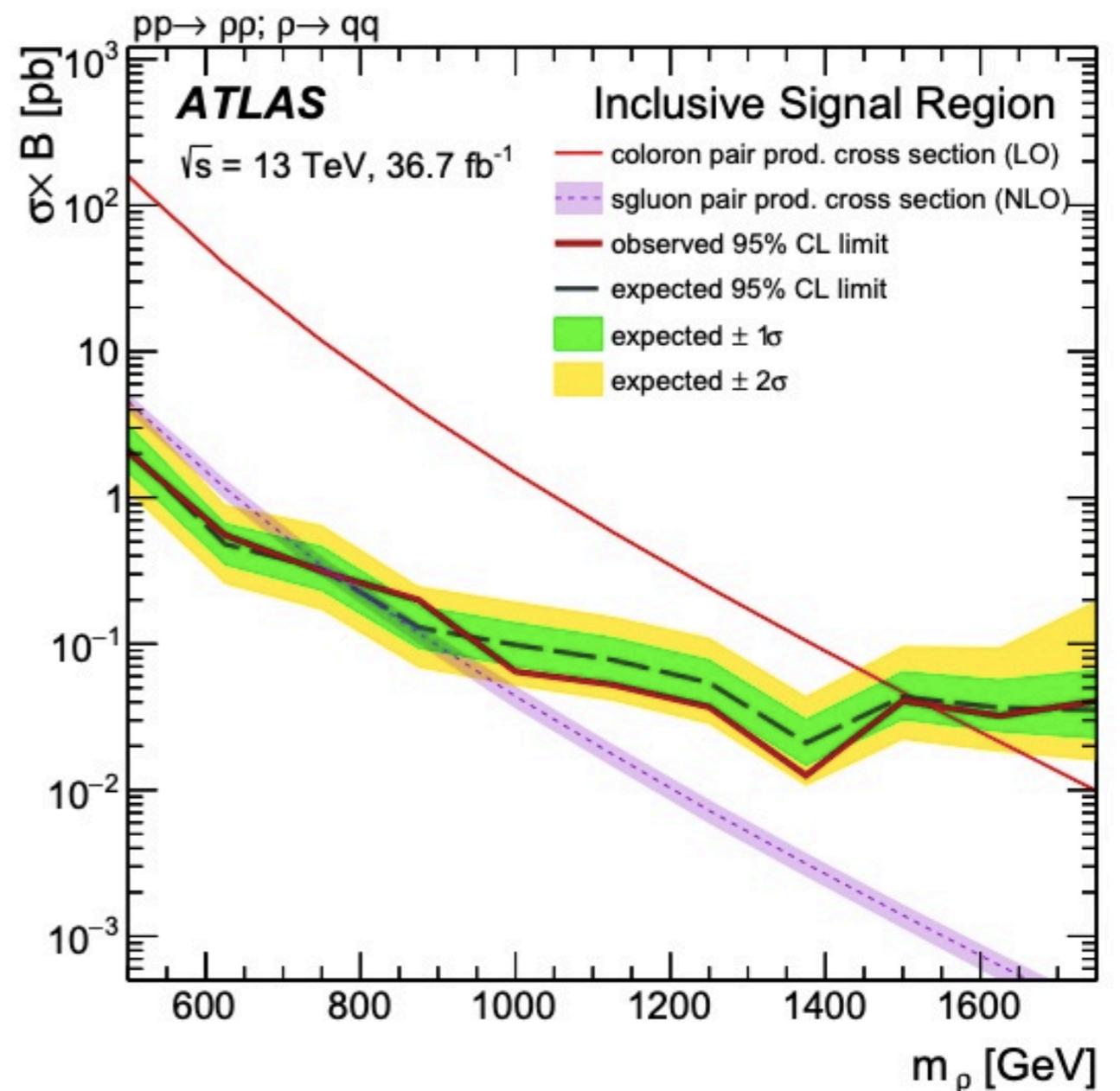


- ❖ We have a bound on color octet scalars

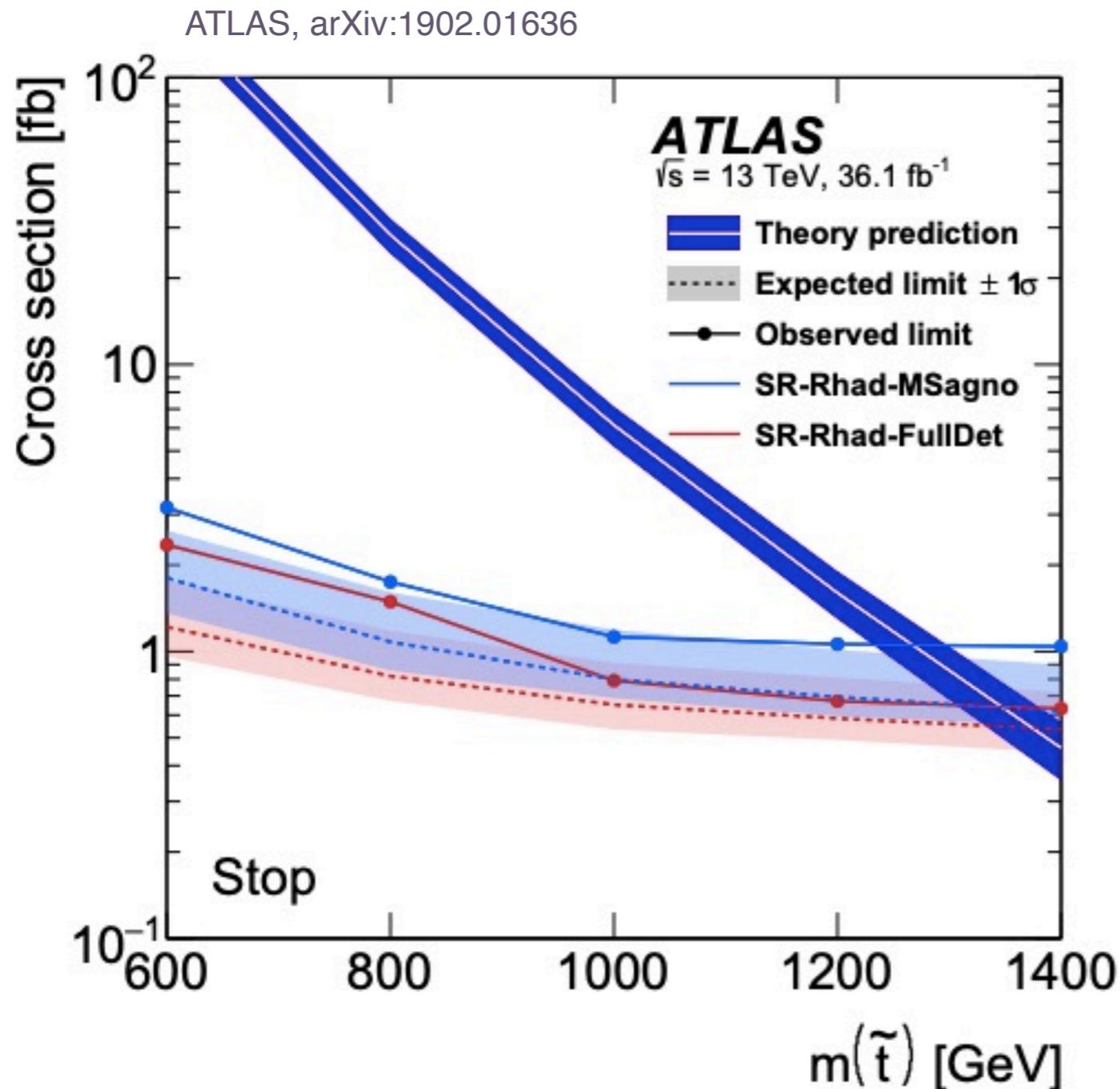
$$m^2(\delta_c) \approx \frac{9}{4\pi} \alpha_{\text{QCD}} \Lambda_{\text{diag}}^2$$

$$\Lambda_{\text{diag}} \gtrsim 2.9 \text{ TeV}$$

ATLAS, arXiv:1710.07171



Collider Phenomenology: R-Hadron Searches



- ❖ We have an updated bound on color triplet scalars

$$m(\pi_d) \gtrsim 1345 \text{ GeV}$$

$$m^2(3_c) \approx \frac{\alpha_c}{\pi} \Lambda_{\text{diag}}^2$$

$$\Lambda_{\text{diag}} \gtrsim 7 \text{ TeV}$$

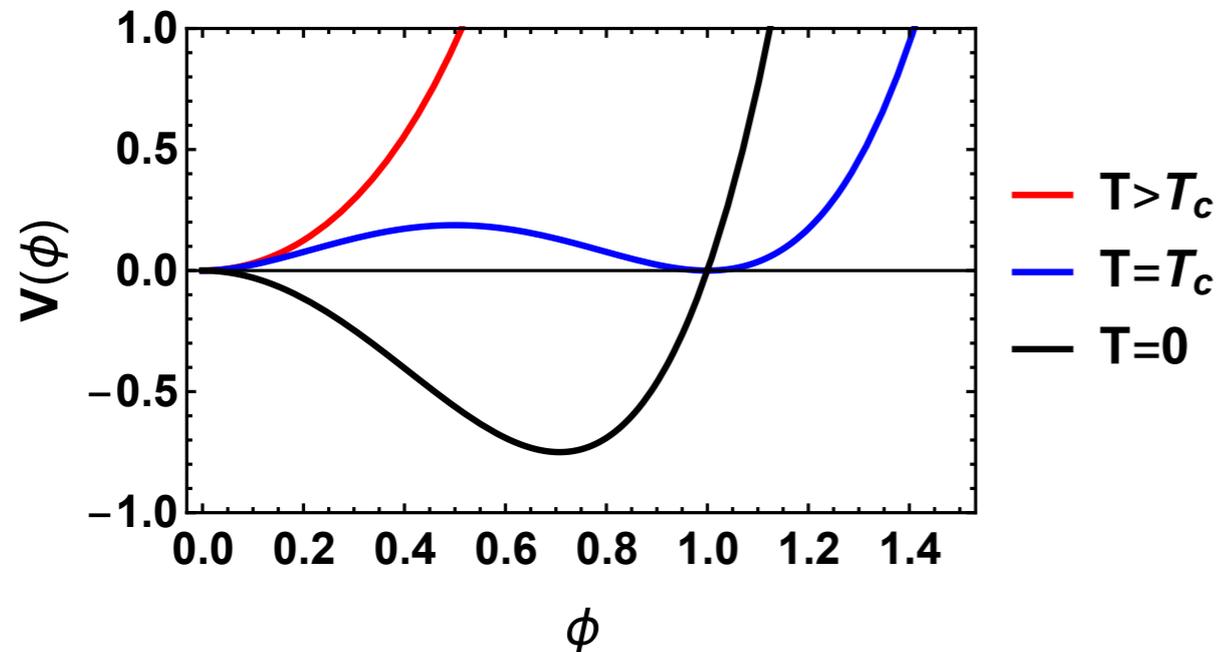
Summary: unification and heavy axions

- ❖ The strong CP problem can be solved using massless quarks and unification

$$SU(6) \times SU(3)' \xrightarrow{\Lambda_{CUT}} SU(3)_{QCD} \times SU(3)_{diag}$$

- ❖ Arrange $\Lambda_{diag} \gg \Lambda_{QCD}$ by decoupling SM quarks ▶ Decoupling the unification partners requires additional model building
- ❖ $\Lambda_{CUT} \gg \Lambda_{diag}$, naturally separated by RG flow
- ❖ Small size instantons provided an extra source of mass for axions
- ❖ Most promising collider signals come from the exotic pions

Gravitational wave phenomenology



- ❖ First order phase transitions can produce gravitational waves Witten (1984) C. Hogan (1986)

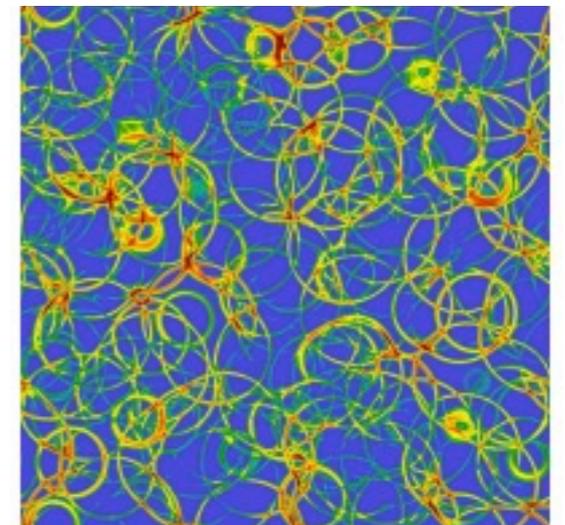
- ❖ Complementary probe of hidden sectors:

- Spontaneous symmetry breaking

J. Jaeckel, V. V. Khoze, P. Schwaller, arXiv:1504.07263
M. Spannowsky, arXiv:1602.03901 D. Croon, V. Sanz, G. White, arXiv:1806.02332

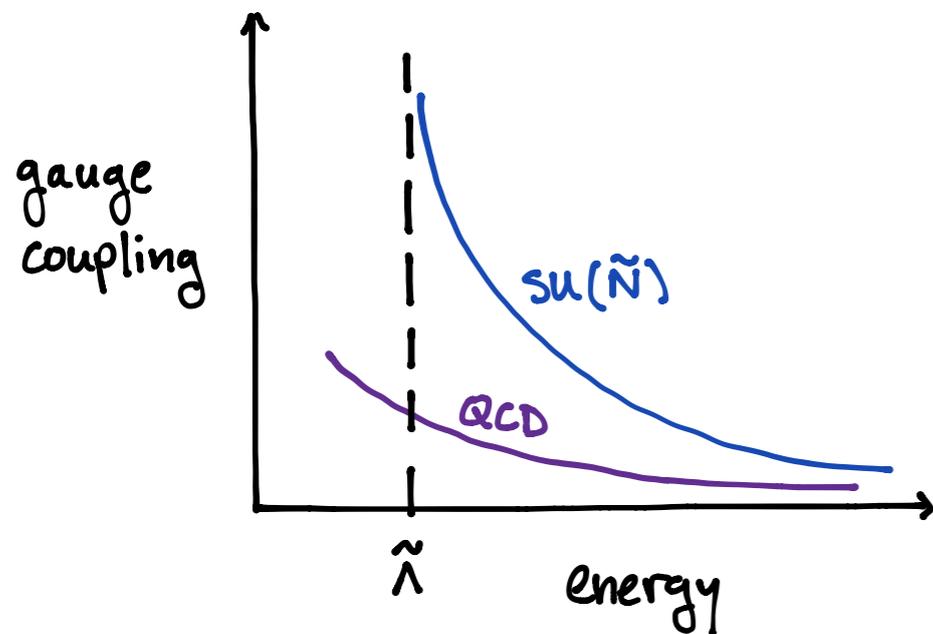
- Confining exotic color sectors

A. J. Helmboldt, J. Kubo, S. van der Woude, arXiv:1904.07891
Y. Bai, A. J. Long, S. Lu, arXiv:1810.04360



M. Hindmarsh, S. Huber, K. Rummukainen, D. Weir, arXiv:1504.03291

Gravitational Waves and Confining Sectors



- ❖ First order phase transition at confinement if $N_F \geq 3$

Pisarski, Wilczek (1984)

- ❖ Gravitational waves can probe confining exotic color sectors

- ❖ Use a low energy effective theory to try and parameterize the behavior of the potential at T_c

- Linear Sigma Model $N_F = 3$

Y. Bai, A. J. Long, S. Lu, arXiv:1810.04360

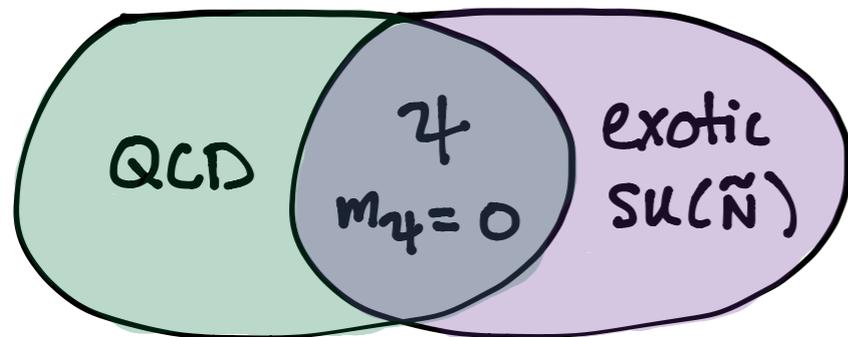
- Nambu-Jona-Lasinio Model $N_F = 3$

A. J. Helmboldt, J. Kubo, S. van der Woude, arXiv: 1904.07891

- ❖ Model building can motivate parameters in the low energy EFT

Generic properties of dynamical axion models

❖ Massless messenger fields



❖ $N_F \geq 3$ at $SU(\tilde{N})$ confinement

❖ First order PT at $\tilde{\Lambda} \sim 3 \text{ TeV}$

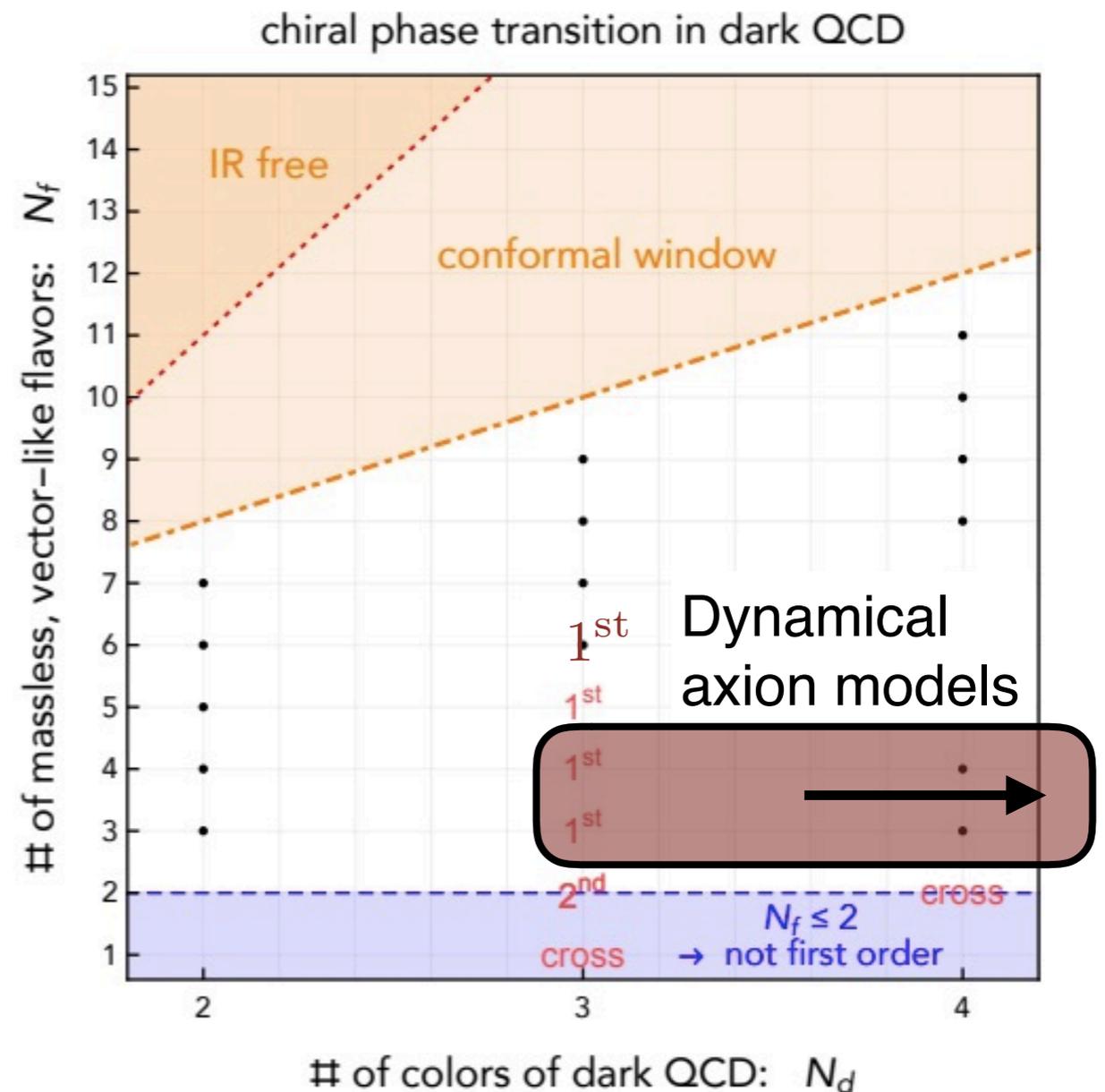
Pisarski, Wilczek (1984)

❖ Quadratically divergent mass terms for pions

$$m^2(\pi) \sim \tilde{\Lambda}^2$$

Plot lifted from: Bai, Long, Lu, arXiv:1810.04360

$N_F = 6$: Iwasaki, Kanaya, Sakai, Yoshié, hep-lat/9504019

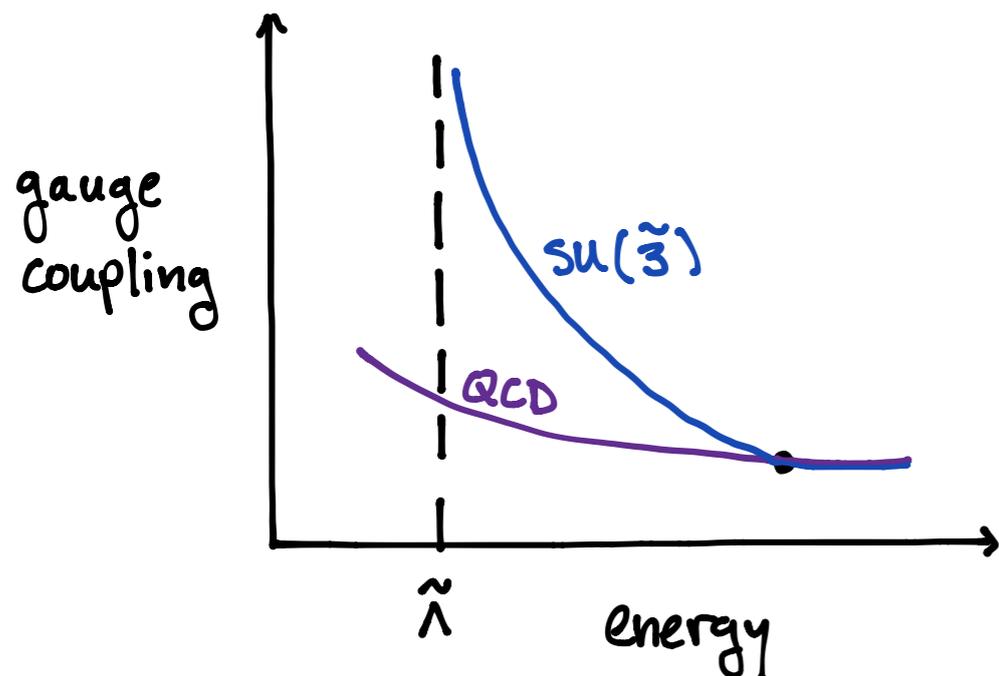


Dynamical Axion Models

$$N_F = 3$$

A. Hook, arXiv:1411.3325

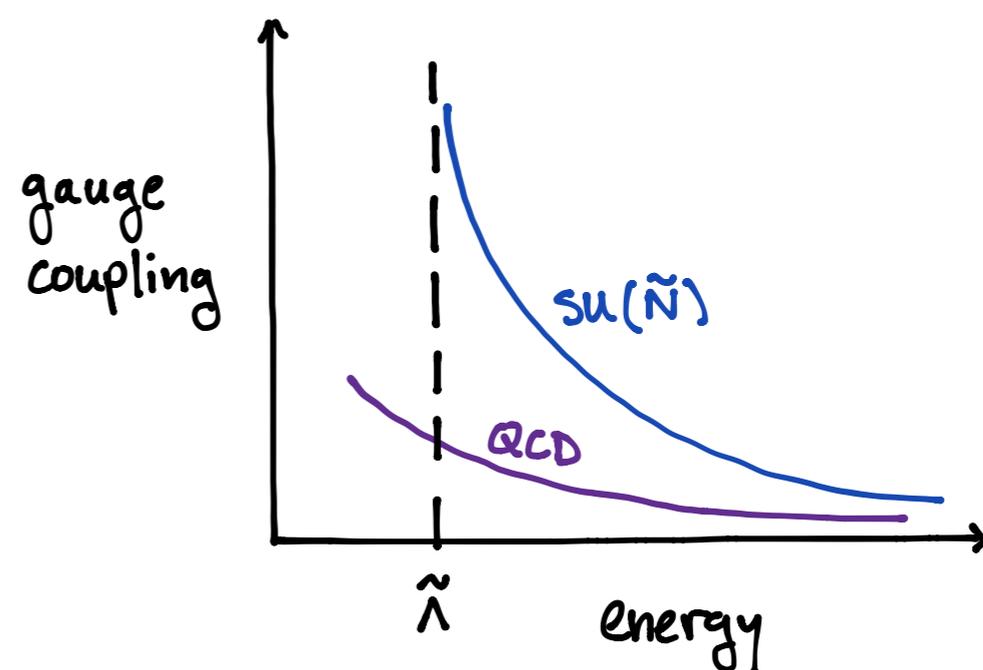
| | $SU(3)_{QCD}$ | $SU(\tilde{3})$ |
|--------|---------------|-----------------|
| ψ | □ | □ |



$$N_F = 4$$

K. Choi, J. E. Kim (1985)

| | $SU(3)_{QCD}$ | $SU(\tilde{N})$ |
|--------|---------------|-----------------|
| ψ | □ | □ |
| χ | 1 | □ |



$SU(\tilde{3})$ confinement $N_F = 3$

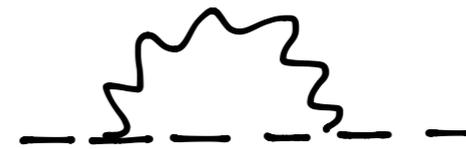
❖ Spontaneous chiral symmetry breaking:

$$SU(3)_L \times SU(3)_R \times U(1)_L \times U(1)_R \rightarrow SU(3)_V \times U(1)_V$$

❖ Resulting Goldstone Bosons: $9 \rightarrow 8_c + 1_c = \pi_8 + \eta'$

Explicit symmetry breaking effects:

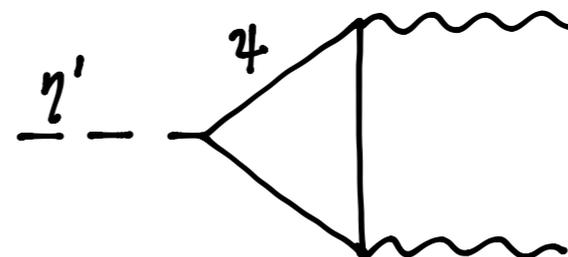
(1) QCD explicitly breaks $SU(3)_V$



$$m^2(\pi_8) \sim \tilde{\Lambda}^2$$

(2) $G\tilde{G}$ explicitly breaks $U(1)_A$

➔ The η' is a **visible dynamical axion**



$$m^2(\eta') \sim \tilde{\Lambda}^2$$

SU(\tilde{N}) confinement $N_F = 4$

Spontaneous symmetry breaking: $U(4)_L \times U(4)_R \rightarrow U(4)_V$

❖ Resulting Goldstone Bosons: $15 + 1 \rightarrow 8_c + 3_c + \bar{3}_c + 1_c + 1_c$
 $= \pi_8 + \pi_3 + \bar{\pi}_3 + \eta'_\psi + \eta'_\chi$

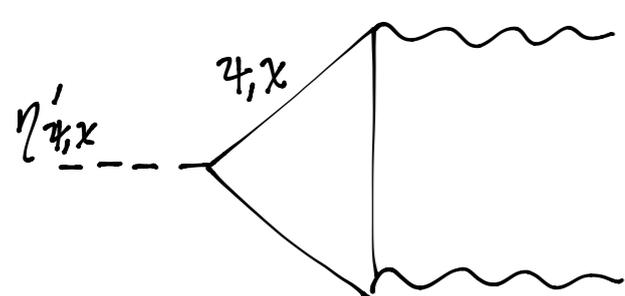
Explicit symmetry breaking effects:

(1) QCD explicitly breaks $SU(4)_V$



$$m^2(\pi_8, \pi_3) \sim \tilde{\Lambda}^2$$

(2) $G\tilde{G}$ explicitly breaks $U(1)_A$



$$m^2(\eta'_1) \sim \tilde{\Lambda}^2$$

$$m(\eta'_2) \tilde{f} \sim m_\pi f_\pi$$

- ❖ The anomaly only gives mass to one η'
- ❖ The light η' is an **invisible dynamical axion**

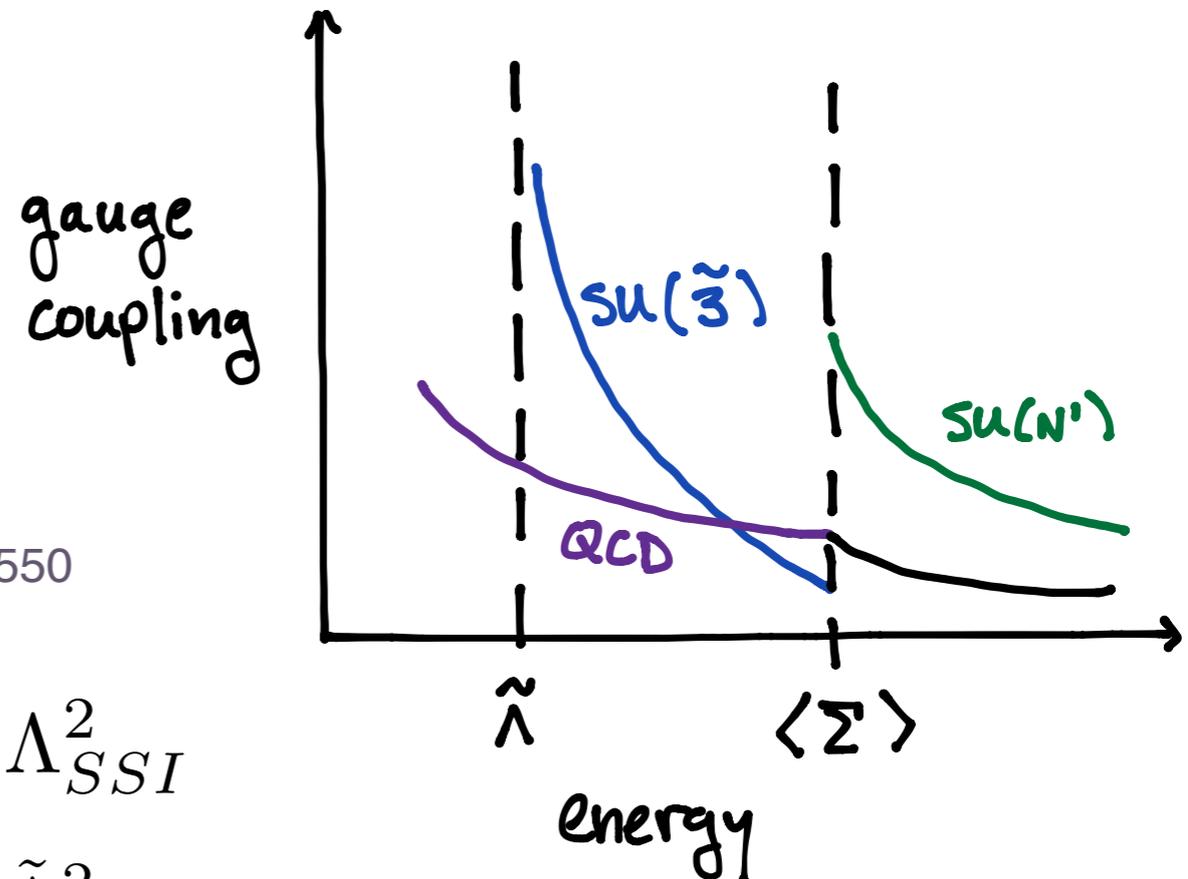
Visible axion models $N_F = 4$

- ❖ New physics at high energies can induce sizable instanton corrections to the axion mass

P. Agrawal, K. Howe arXiv:1710.04213, 1712.05803

J. Fuentes-Martin, M. Reig, A. Vicente, arXiv:1907.02550

$$\begin{array}{ccc}
 m^2(\eta'_1) \sim \tilde{\Lambda}^2 & & m^2(\eta'_1) \sim \Lambda_{SSI}^2 \\
 m(\eta'_2) \sim m_\pi \frac{f_\pi}{\tilde{f}} & \rightarrow & m^2(\eta'_2) \sim \tilde{\Lambda}^2
 \end{array}$$



MK Gaillard, B. Gavela, RH,
P. Quilez, R. del Rey, arXiv:1805.06465

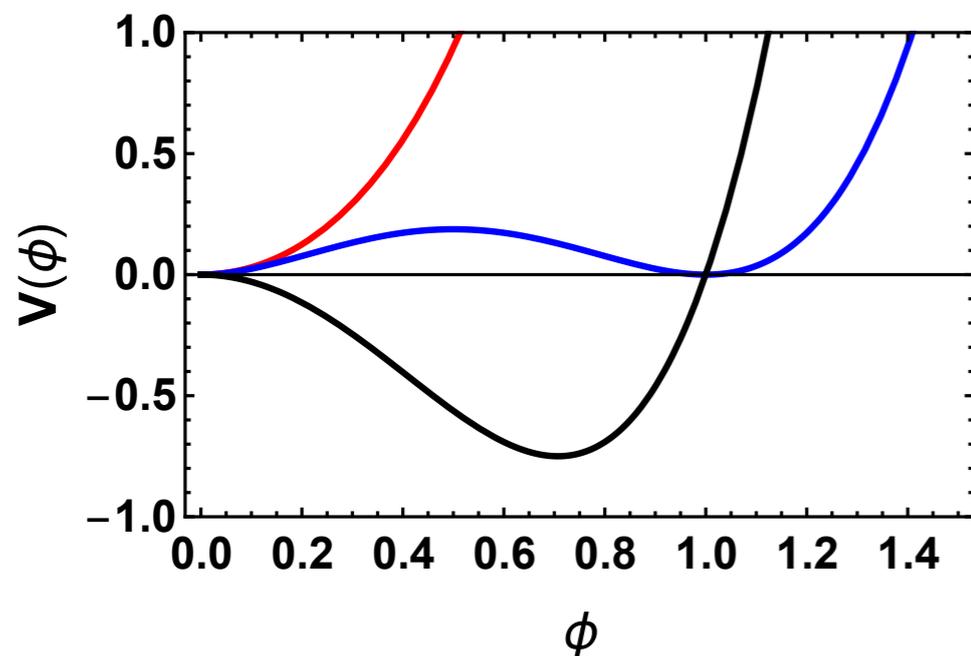
- ❖ Possible to have a combination of anomalous effects raise the mass of the lightest η'

Phase transition at confinement

- ❖ Model the phase transition using the linear sigma model

$$V(\Sigma) = -m_\Sigma^2 \text{Tr}(\Sigma\Sigma^\dagger) + \frac{\lambda}{2} [\text{Tr}(\Sigma\Sigma^\dagger)]^2 + \frac{\kappa}{2} (\Sigma\Sigma^\dagger\Sigma\Sigma^\dagger),$$

- ❖ Spontaneous chiral symmetry breaking $\Sigma_{ij} \sim \langle \bar{\psi}_{Rj} \psi_{Li} \rangle$



$$\Sigma_{ij} = \frac{\varphi + i\eta'}{\sqrt{2N_F}} \delta_{ij} + X^a T_{ij}^a + i\pi^a T_{ij}^a$$

$$\langle \varphi \rangle = 0, \quad T \gg 0 \quad \text{Chiral symmetry restored}$$

$$\langle \varphi \rangle = f_\Sigma, \quad T \leq T_c \quad \text{Chiral symmetry}$$

Phase transition at confinement

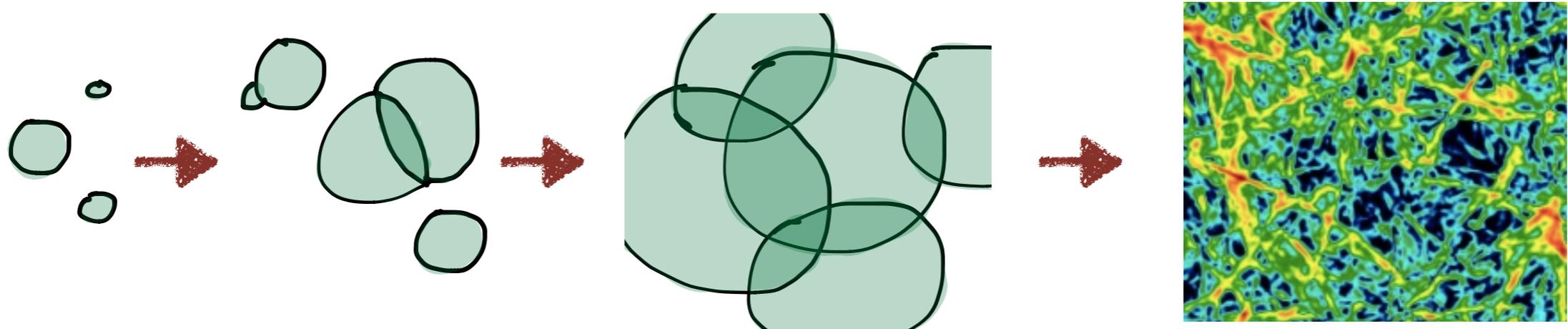
- ❖ Symmetry breaking parameters μ_Σ , ξ , μ_{SSI} determine the masses of the pNGB's π and η'

$$V(\Sigma) = -m_\Sigma^2 \text{Tr}(\Sigma\Sigma^\dagger) + \frac{\lambda}{2} [\text{Tr}(\Sigma\Sigma^\dagger)]^2 + \frac{\kappa}{2} (\Sigma\Sigma^\dagger\Sigma\Sigma^\dagger),$$

- $-(\mu_\Sigma \det\Sigma + h.c.)$ ← Include the explicit $U(1)_A$ symmetry breaking from instanton effects
- $-\xi \text{Tr} Q^a \Sigma\Sigma^\dagger Q^{a\dagger}$ ← Include the explicit symmetry breaking from QCD charges
- $-\mu_{SSI} \text{Tr}(P_\chi \Sigma P_\chi \Sigma^\dagger P_\chi)$ ← Include the new mass contributions from small-sized instantons

Phase transition in the early universe

- ❖ Dynamics from tunneling to the $T = 0$ vacuum



D. Weir, “The sound of gravitational waves from a [confinement] phase transition,” saoghal.net/slides/ectstar/

$$\Omega_{GW}|_{\text{peak}} = \Omega_{GW} \left(\alpha, \frac{\beta}{H} \right)$$

$$\alpha = \text{Latent heat, } \frac{\Delta\mathcal{L}}{\rho_{\text{rad}}}$$

$$\frac{\beta}{H} = \text{Parameterizes speed of the phase transition}$$

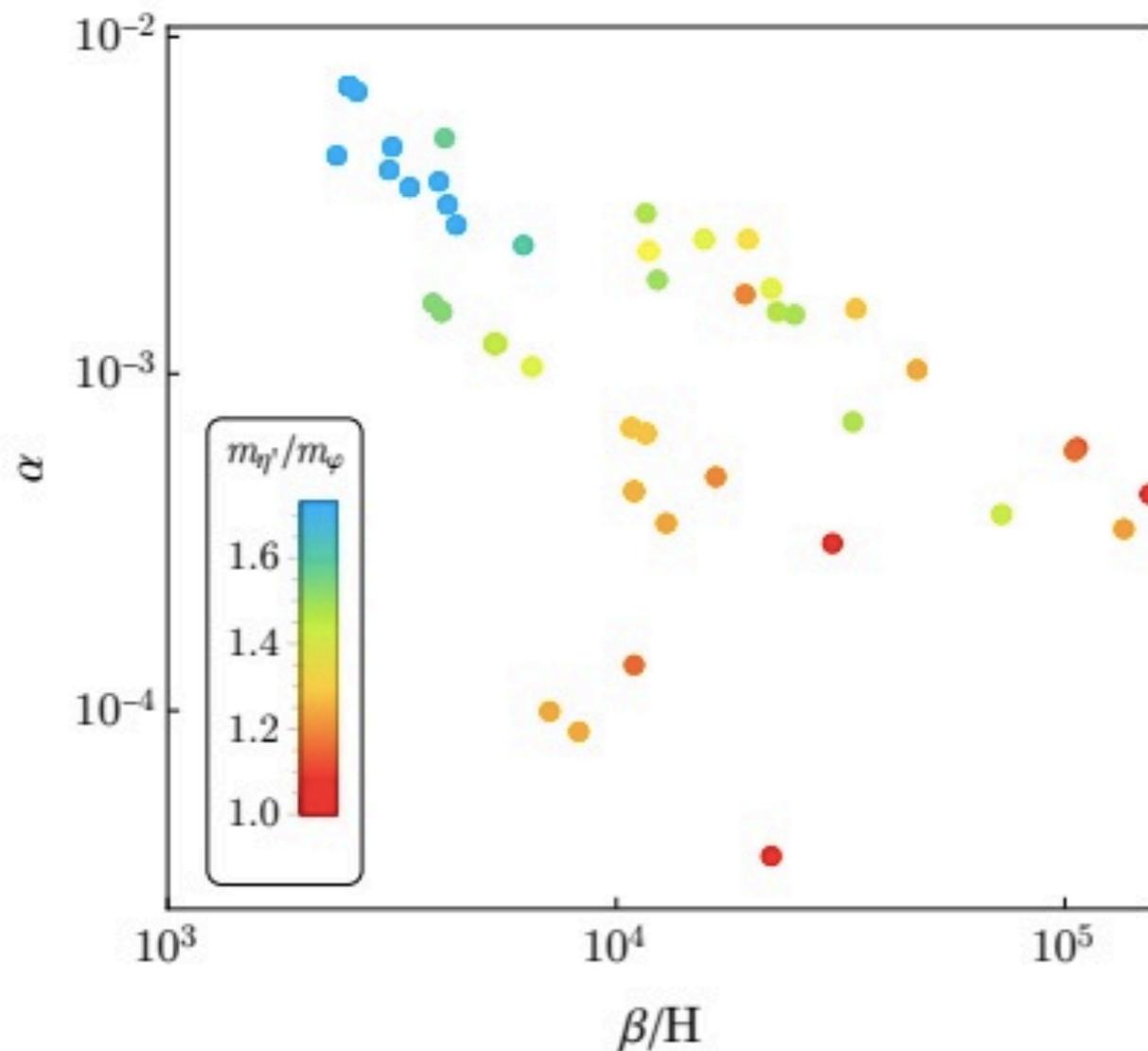
$$f_{GW}|_{\text{peak}} = f_{GW} \left(T_N, \frac{\beta}{H} \right)$$

$$T_N = \text{Nucleation temperature}$$

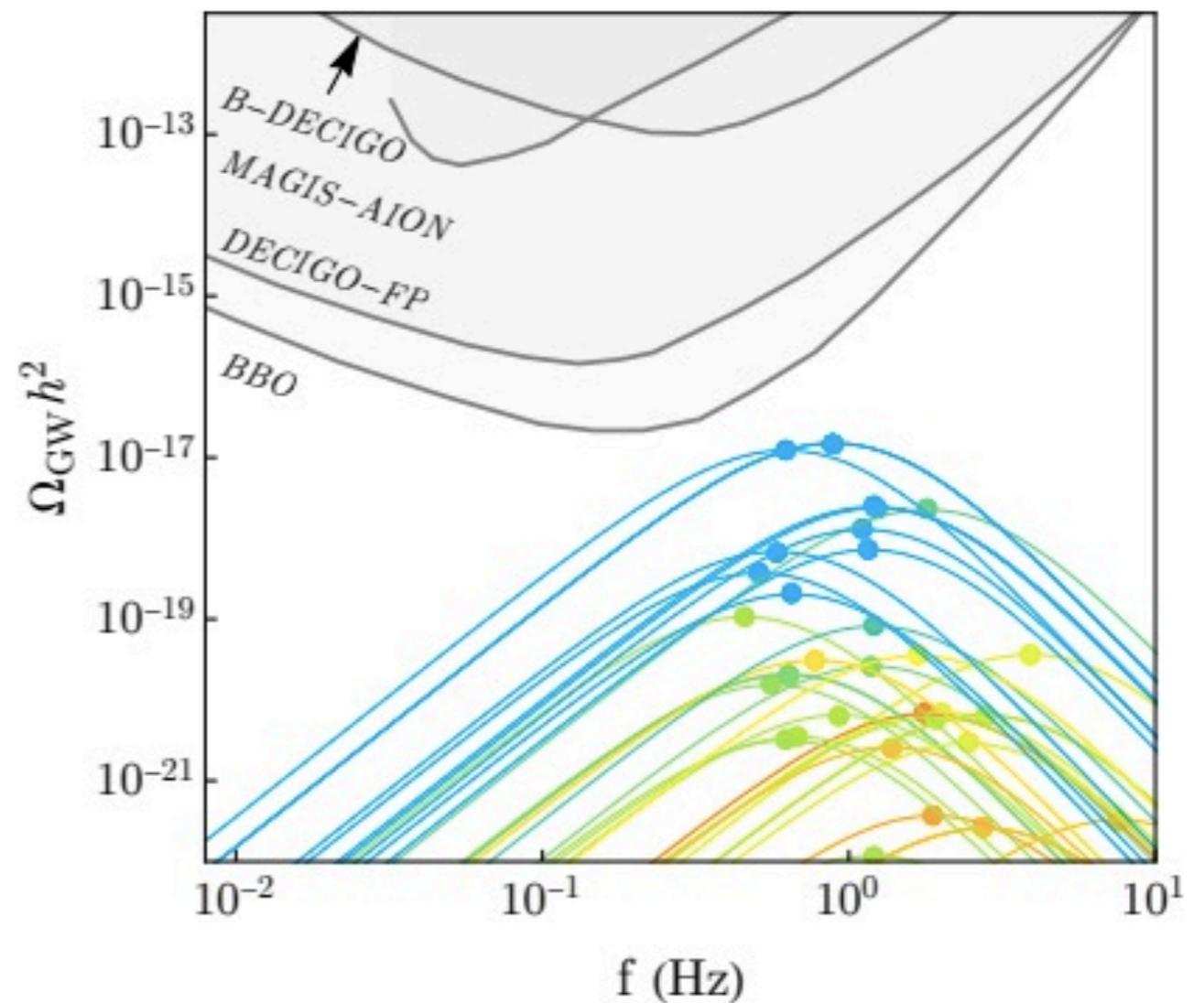
Gravitational wave signal $N_F = 3$

D. Croon, RH, V. Sanz, arXiv:1904.10967

Thermal parameters



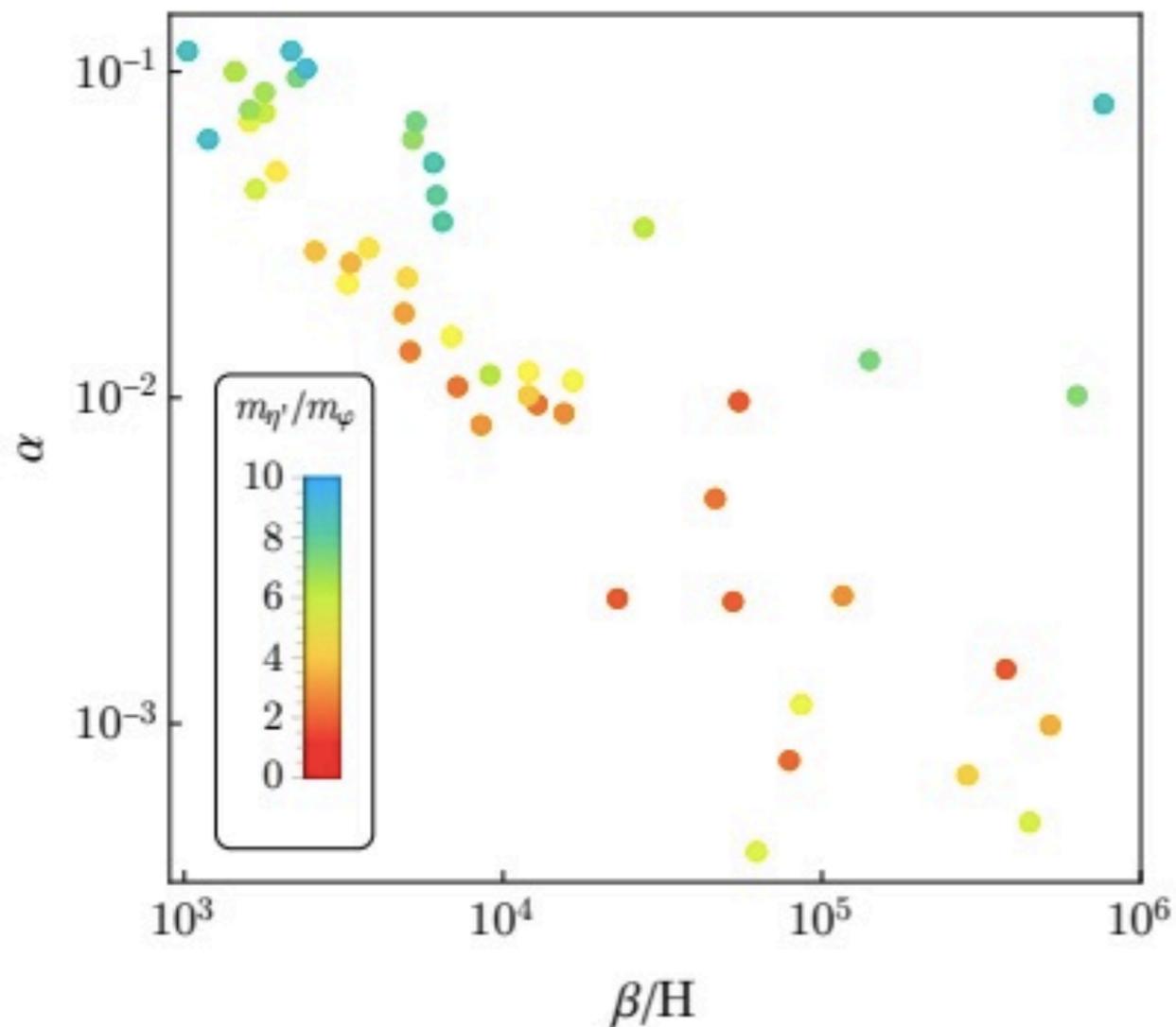
GW signal $\tilde{\Lambda} \sim 3$ TeV



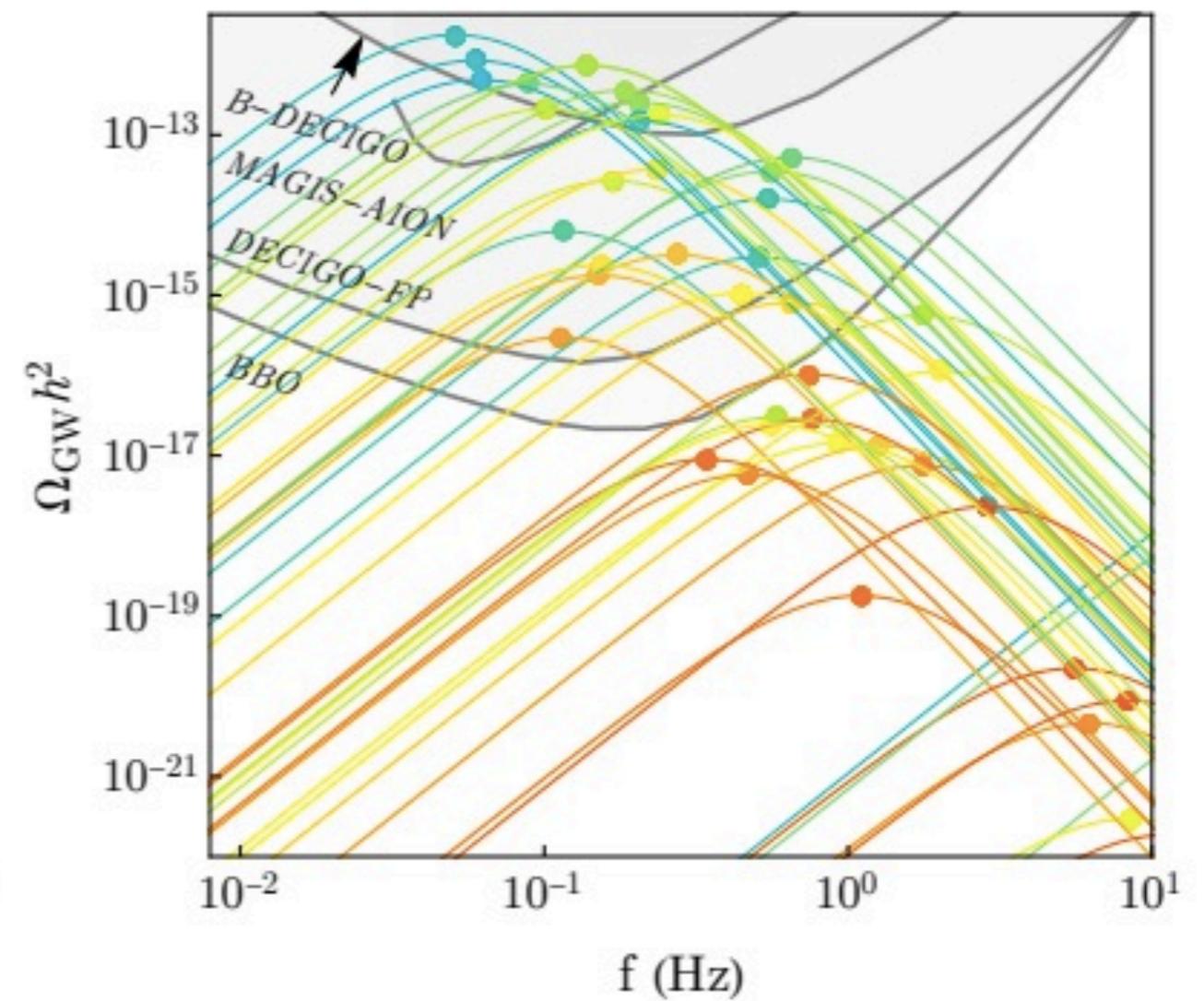
Gravitational wave signal $N_F = 4$

D. Croon, RH, V. Sanz, arXiv:1904.10967

Thermal parameters

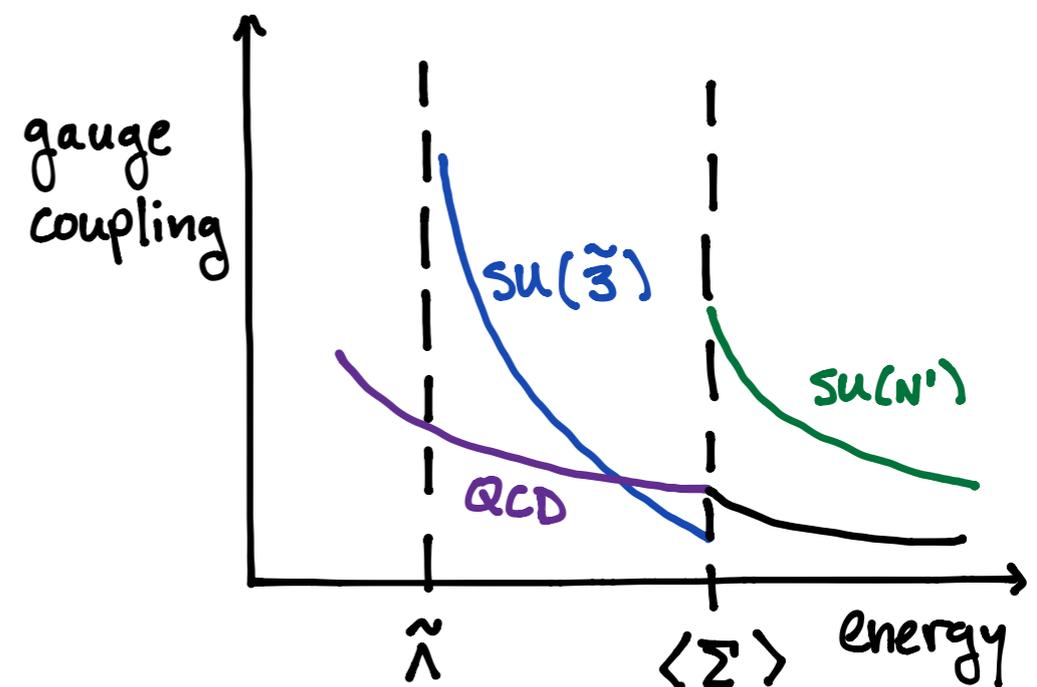


GW signal $\tilde{\Lambda} \sim 3$ TeV



Summary: Gravitational Wave Signal

- ❖ Prospects for gravitational wave signals for dynamical axion models with $\tilde{\Lambda} \sim 3 \text{ TeV}$
- ❖ The gravitational wave signature is sensitive to the explicit $U(1)_A$ breaking parameter μ_Σ in the linear sigma model
- ❖ GW signal favors models where high energy effects of extra color groups provide another source of axion mass



Conclusions

❖ Extra color groups provide a window to richer phenomenology

❖ Visible axions $m_a^2 f_a^2 \approx m_\pi^2 f_\pi^2 \longrightarrow + \sim \Lambda_{\text{new}}^4$

❖ Massless quarks still viable



❖ Symmetries are usually needed to reduce the number the CP violating phases

❖ High energy effects of extra color groups can provide another source of axion mass

Thank you!

Back-up Slides

Temperature dependence of μ_Σ

- ❖ The size of the $\mu_\Sigma \det \Sigma$ term is important for the GW signal

$$m_{\eta'} \sim \mu_\Sigma$$

- ❖ Explicit $U(1)_A$ breaking comes from instantons G. 't Hooft (1976)

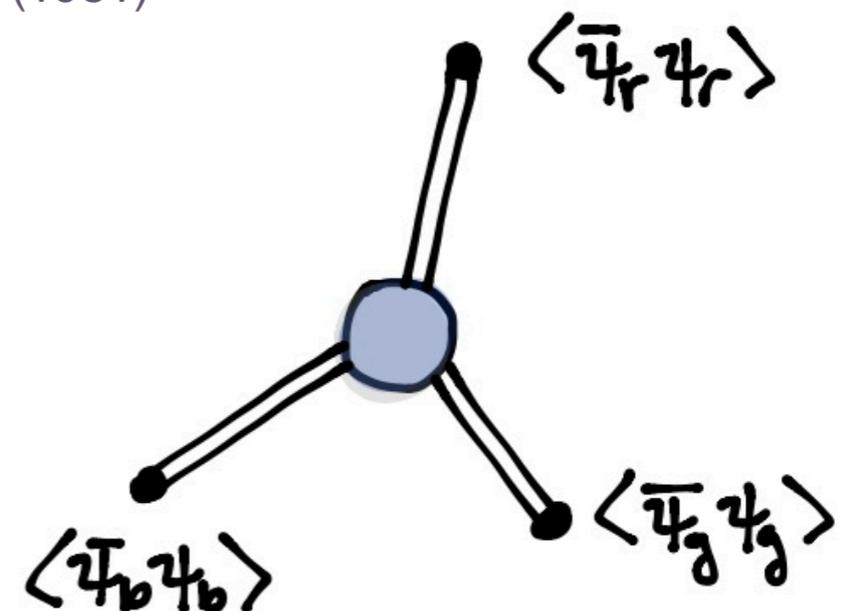
- ❖ When $T \gg T_c$ and g_{QCD} is perturbative, the dilute instanton gas approximation holds Gross, Pisarski, Yaffe, (1981)

- ❖ For example, when the axion mass is lifted by small size instanton effects:

$$m_{\eta'} \sim \frac{\Lambda_{SSI}^2}{\tilde{f}} \sim \tilde{f}^6 \int d\rho \rho^4 d(\rho, T)$$

M. A. Shifman, A. I. Vainshtein, V. I. Zakharov (1980)

Callan, Dashen, Gross, (1978)



Temperature dependence of μ_Σ

- ❖ A related parameter is the topological susceptibility

$$\chi(T) = \int \frac{d\rho}{\rho^5} d(\rho, T) \quad \rightarrow \quad m_{\eta'} \sim \tilde{f}^6 \int d\rho \rho^4 d(\rho, T)$$

D. Croon, R. Houtz, V. Sanz, arXiv:1904.10967

- ❖ Studied by the lattice community

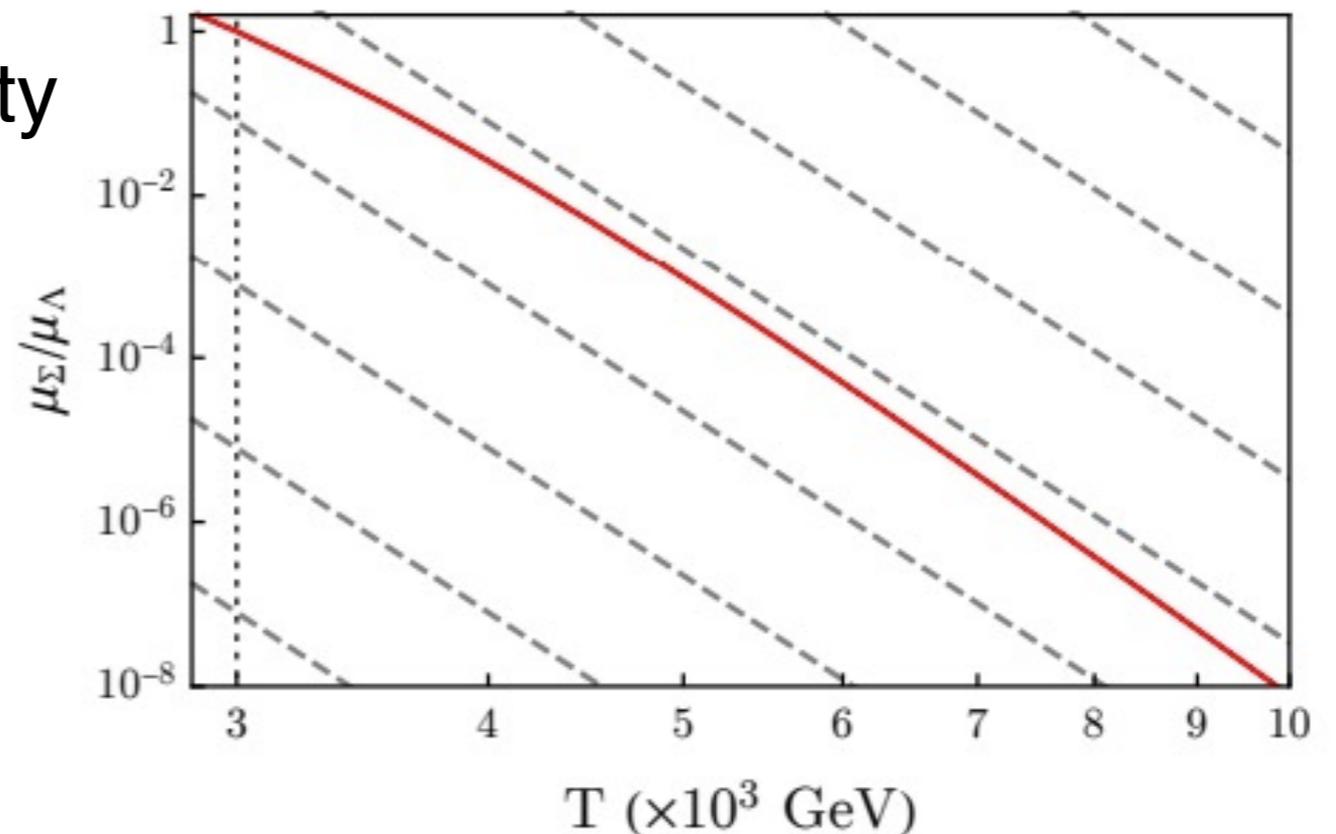
$$\chi(T) \sim T^{-8} \quad \rightarrow$$

J. Frison, R. Kitano, H. Matsufuru, S. Mori, N. Yamada, arXiv:1606.07175

M. Dine, P. Draper, L. Stephenson-Haskins, D. Xu, arXiv:1705.00676

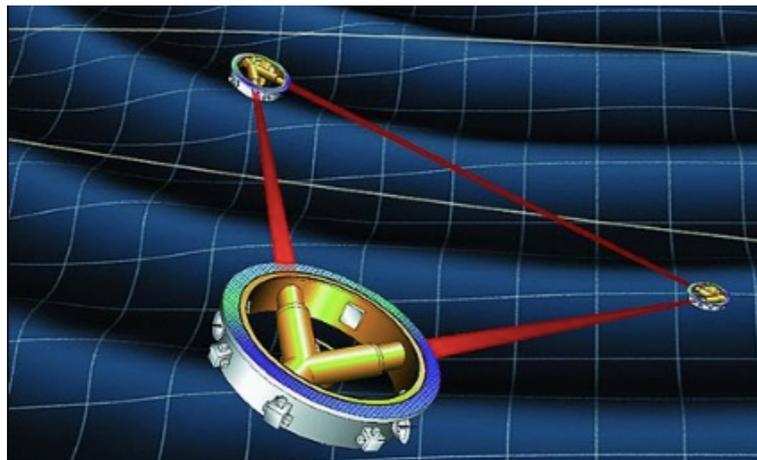
- ❖ DGA breaks down near confinement

- ❖ Does μ_Σ contribute significantly during the phase transition?

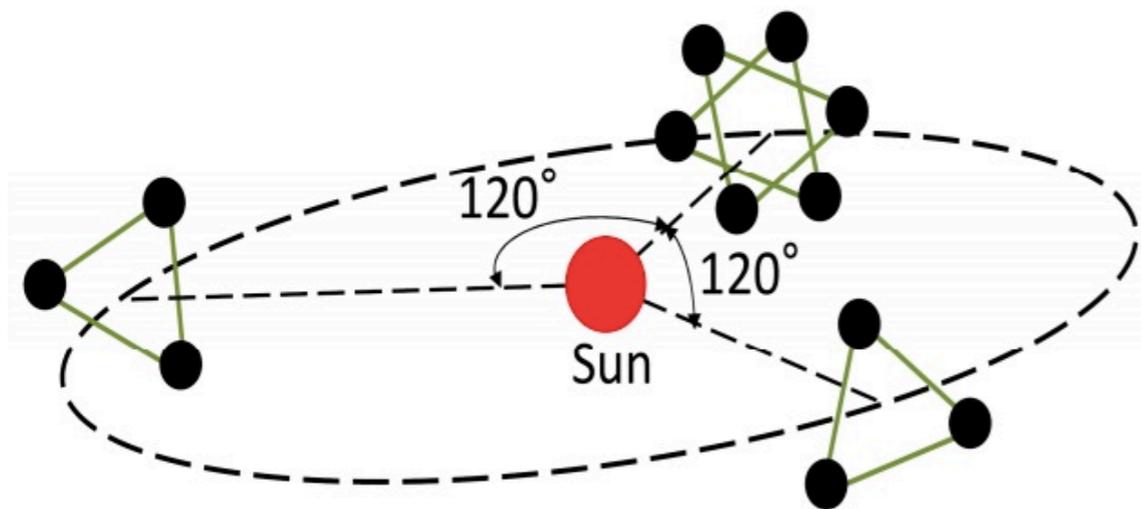


Future gravitational wave detectors

- ❖ Laser interferometers LISA, B-DECIGO, DECIGO and BBO



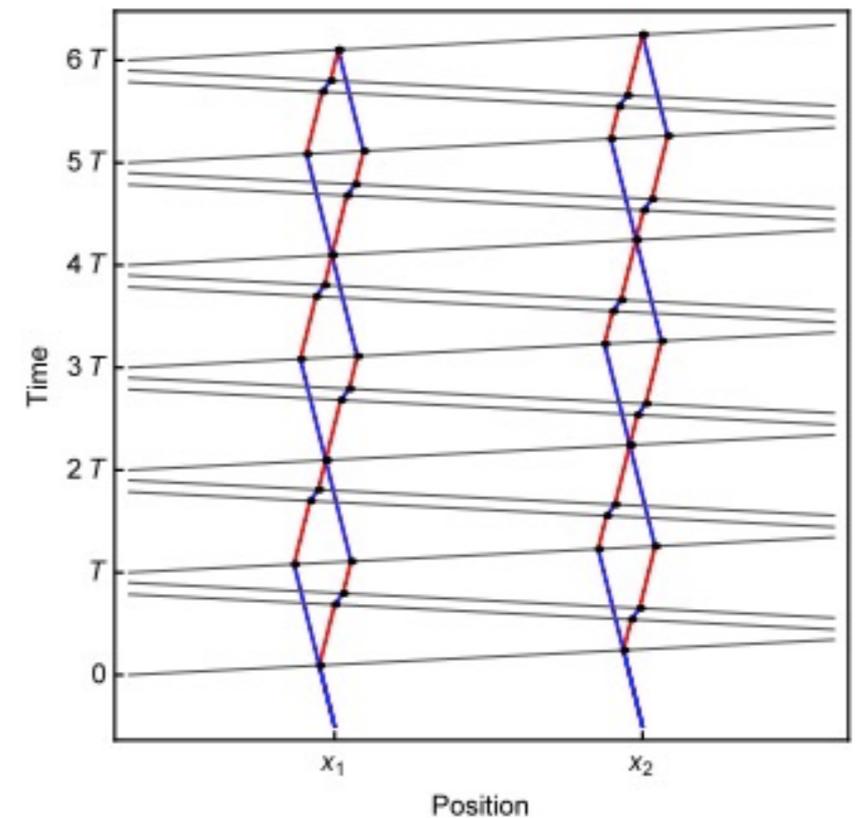
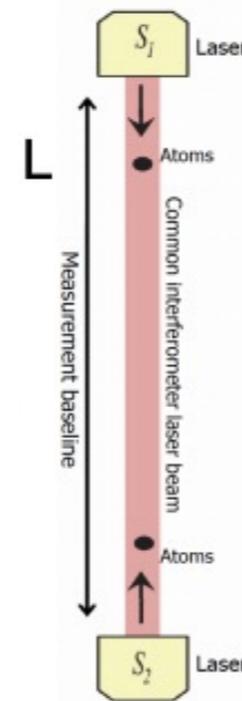
NASA illustration of LISA (from Wikipedia)



Yagi, 1302.2388

- ❖ Atom interferometers AION and MAGIS

Graham, Hogan, Kasevich, Rajendran, arXiv:1606.01860



Buchmueller, "A UK AION for the exploration of ultra-light dark matter and mid-frequency gravitational waves" (2018)

Is a heavy axion consistent?

So... did we cheat?

- ❖ It's weird to have an axion bigger than the QCD confinement scale...



- ❖ You can't impose a symmetry on a boundary condition.
- ❖ θ can be interpreted as a constant electric field. The axion solution \sim screening the field.

Dvali, hep-th/0507215

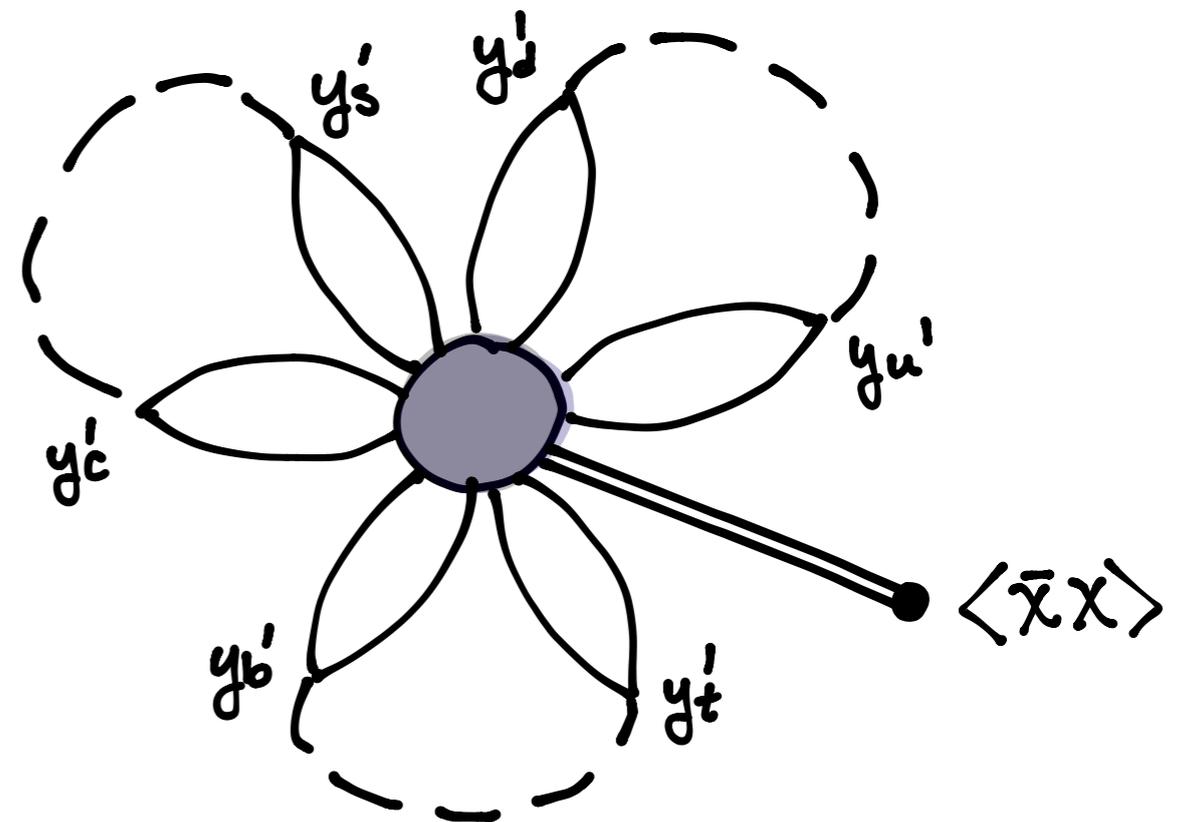
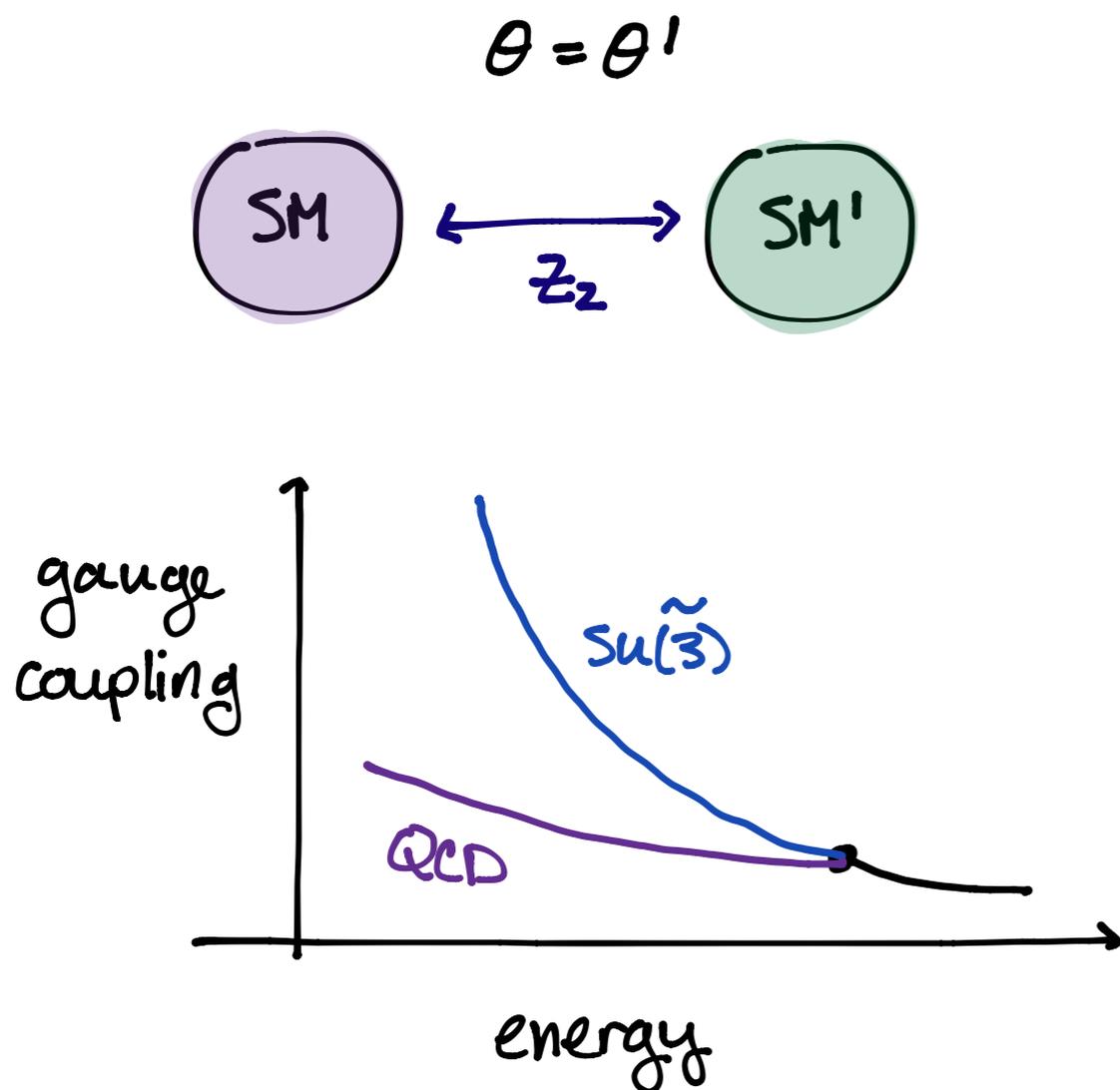
- ❖ You can solve the strong CP problem at high energies M.K. Gaillard, J. Ellis (1979)
- ❖ Nelson-Barr Mechanism A. Nelson (1984)
S.M. Barr (1984)

So... did we cheat?

Two model-building ingredients give a heavy axion:

Symmetry that relates θ 's

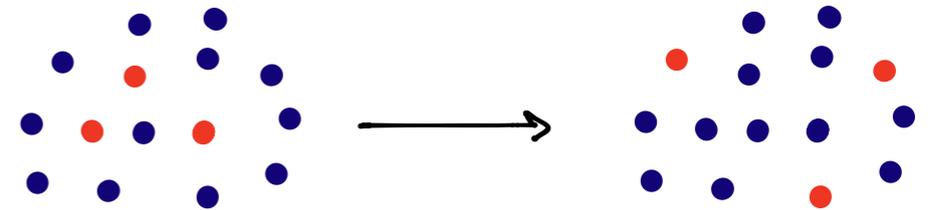
Extra mass contributions



Boundary condition vs. symmetry

Is θ a boundary condition and not a coupling?

❖ Example: Baryon Asymmetry



❖ This question applies to the Z_2 mirror world picture.



In unification, the two θ angles came from the same origin.

$$\frac{\alpha_6}{8\pi} \theta_6 G_6 \tilde{G}_6 \rightarrow \frac{\alpha_c}{8\pi} \theta_6 G_{QCD} \tilde{G}_{QCD} + \frac{\alpha_{\text{diag}}}{8\pi} \theta_6 G_{\text{diag}} \tilde{G}_{\text{diag}}$$

Screening in the dual picture

$$\mathcal{L} \ni \frac{\alpha}{8\pi} \theta G \tilde{G} \quad \longrightarrow \quad \mathcal{L} \ni \theta F \quad \text{G. Dvali, hep-th/0507215}$$

- ❖ This term is a total derivative $G \tilde{G} = \partial_\mu K^\mu$

$$K^\mu = \frac{\alpha}{8\pi} \epsilon^{\mu\alpha\beta\gamma} \text{Tr} \left(A_{[\alpha} A_\beta A_{\gamma]} - \frac{2}{3} A_{[\alpha} \partial_\beta A_{\gamma]} \right)$$

- ❖ You can write this current in terms of a composite three form

$$K^\mu = \epsilon^{\mu\alpha\beta\gamma} C_{\alpha\beta\gamma}$$

- ❖ Then this F is just the field strength of the three form field

$$\partial_\mu C_{\alpha\beta\gamma} \equiv F_{\mu\alpha\beta\gamma} \quad \epsilon^{\mu\alpha\beta\gamma} F_{\mu\alpha\beta\gamma} = F$$

Screening in the dual picture

$$\mathcal{L} \ni \frac{\alpha}{8\pi} \theta G \tilde{G} \quad \longrightarrow \quad \mathcal{L} \ni \theta F$$

G. Dvali, hep-th/0507215

- ❖ Consider a theory of just the massless $C_{\alpha\beta\gamma}$ field

$$\mathcal{L} = \frac{1}{\Lambda^4} F_{\mu\alpha\beta\gamma} F^{\mu\alpha\beta\gamma} + C_{\alpha\beta\gamma} J^{\alpha\beta\gamma}$$

- ❖ Without sources, the EOM gives $\partial^\mu F_{\mu\alpha\beta\gamma} = 0$

$$F_{\mu\alpha\beta\gamma} = F_0 \epsilon_{\mu\alpha\beta\gamma} = \theta \Lambda^4 \epsilon_{\mu\alpha\beta\gamma}$$

An arbitrary value of this would satisfy the EOM

Screening in the dual picture

$$\mathcal{L} \ni \frac{\alpha}{8\pi} \theta G \tilde{G} \quad \longrightarrow \quad \mathcal{L} \ni \theta F$$

G. Dvali, hep-th/0507215

- ❖ Consider a theory of just the massless $C_{\alpha\beta\gamma}$ field

$$\mathcal{L} = \frac{1}{\Lambda^4} F_{\mu\alpha\beta\gamma} F^{\mu\alpha\beta\gamma} + C_{\alpha\beta\gamma} J^{\alpha\beta\gamma}$$

- ❖ Without sources, the EOM gives $\partial^\mu F_{\mu\alpha\beta\gamma} = 0$

$$F_{\mu\alpha\beta\gamma} = F_0 \epsilon_{\mu\alpha\beta\gamma} = \theta \Lambda^4 \epsilon_{\mu\alpha\beta\gamma}$$

- ❖ Rewriting the kinetic term:

$$\frac{1}{\Lambda^4} F_{\mu\alpha\beta\gamma} F^{\mu\alpha\beta\gamma} = \theta \epsilon_{\mu\alpha\beta\gamma} F^{\mu\alpha\beta\gamma} = \theta F$$

Screening in the dual picture

$$\mathcal{L} \ni \frac{\alpha}{8\pi} \theta G \tilde{G} \quad \longrightarrow \quad \mathcal{L} \ni \theta F \quad \text{G. Dvali, hep-th/0507215}$$

- ❖ You can think of F as the kinetic term for $C_{\alpha\beta\gamma}$ with a constant electric field values, and the the strength of that electric field θ
- ❖ Screening this electric field would ensure $\theta = 0$
- ❖ This can be accomplished by giving $C_{\alpha\beta\gamma}$ a mass

Screening in the dual picture

These two theories are dual to each other:

G. Dvali, hep-th/0507215

$$\mathcal{L}_B = \frac{3}{f_a} (\partial_\alpha B_{\beta\gamma} - C_{\alpha\beta\gamma})^2 + \frac{1}{\Lambda^4} F_{\mu\alpha\beta\gamma} F^{\mu\alpha\beta\gamma}$$

Stückelberg
field

$$\mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a + \left(\theta + \frac{a}{f_a} \right) F$$

- ❖ The axion dynamically ensuring $\left\langle \theta + \frac{a}{f_a} \right\rangle = 0$ is dual to “Higgsing” the three-form gauge field and screening its electric field

The screening effect & unification

$$\mathcal{L} \ni \frac{\alpha_1}{8\pi} \theta_1 G_1 \tilde{G}_1 + \frac{\alpha_2}{8\pi} \theta_2 G_2 \tilde{G}_2 \longrightarrow \mathcal{L} \ni \theta_1 F_1 + \theta_2 F_2$$

If you assume unification, you have a single parameter: $\theta_1 = \theta_2$

- ❖ The parameter that governs the strength of the electric field is then the same for both gauge groups

$$F_{\mu\alpha\beta\gamma} = F_0 \epsilon_{\mu\alpha\beta\gamma} = \theta \Lambda^4 \epsilon_{\mu\alpha\beta\gamma}$$

- ❖ Given a single axion, are both electric fields screened in the dual picture?

The screening effect & unification

These two theories are dual to each other:

G. Dvali, hep-th/0507215

$$\mathcal{L}_B = \frac{3}{f_a} \left(\partial_\alpha B_{\beta\gamma} - C_{1\alpha\beta\gamma} - C_{2\alpha\beta\gamma} \right)^2 + \frac{1}{\Lambda_1} \theta F_1 + \frac{1}{\Lambda_2} \theta F_2$$

Stückelberg
field

$$\mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a + \left(\theta + \frac{a}{f_a} \right) (F_1 + F_2)$$

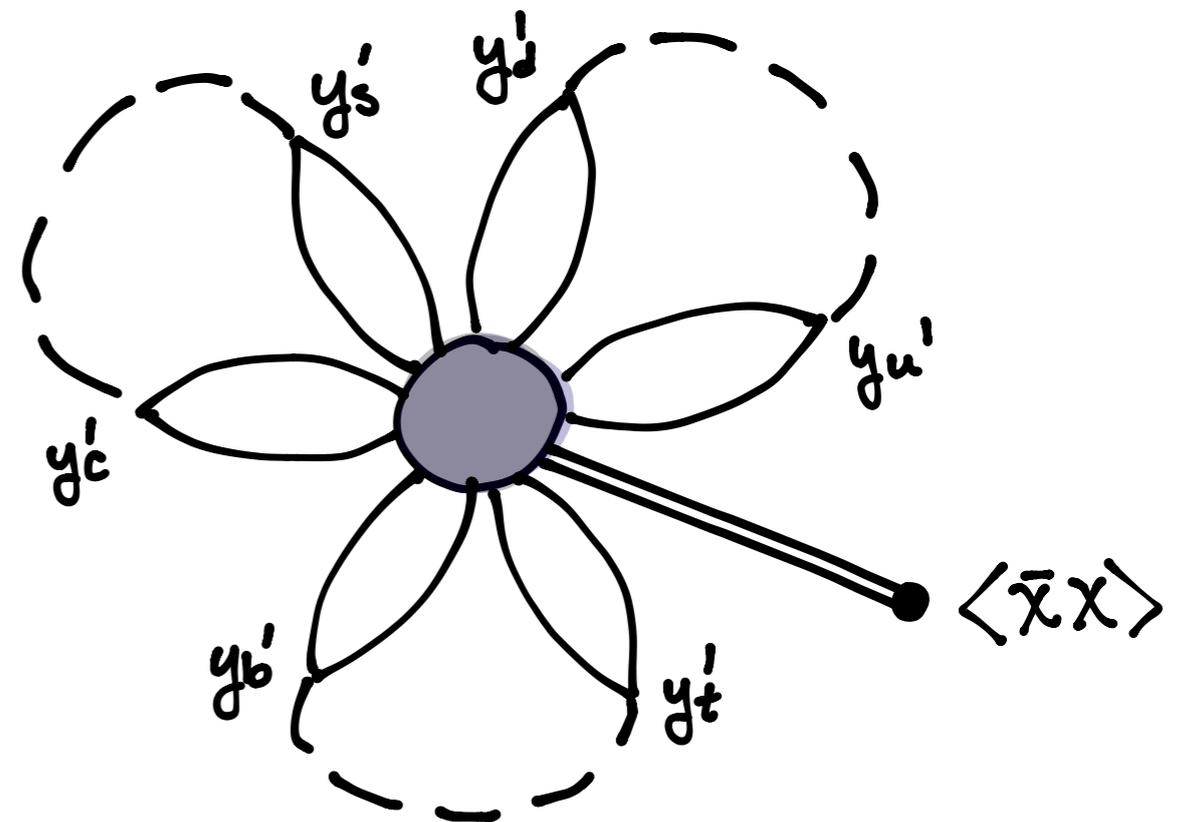
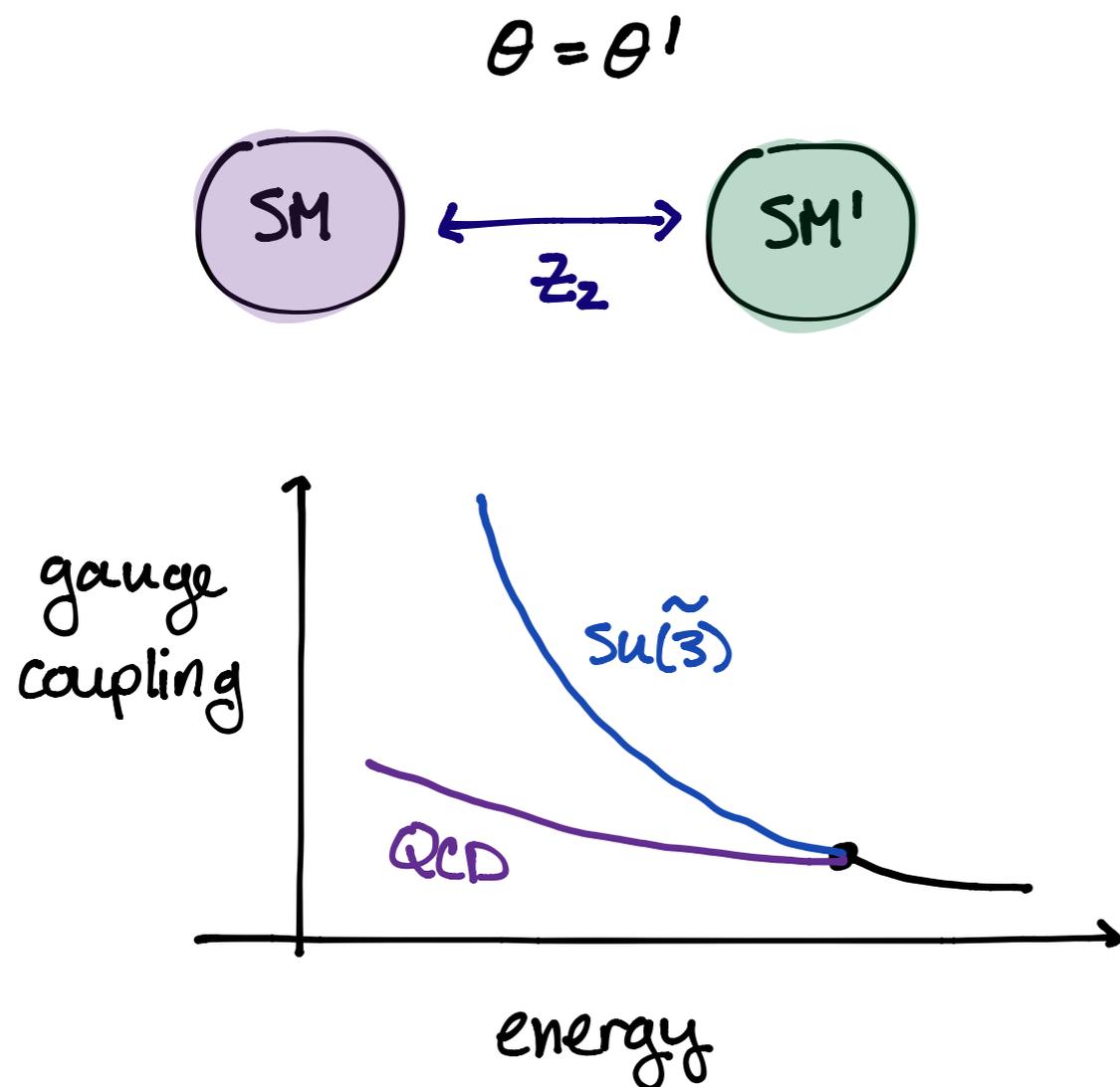
- ❖ Only the combination of $F_1 + F_2$ gets screened
- ❖ The value of $F_1 - F_2$ is not screened, but is guaranteed to be zero when we set $\theta_1 = \theta_2$

So... did we cheat?

Two model-building ingredients give a heavy axion:

✓ Symmetry that relates θ 's

Extra mass contributions



More Back-up Slides

Two UV Completions

(1) Add a second massless quark charged under $SU(3)'$

$$m_\chi = 0$$

| | $SU(6)$ | $SU(3)'$ |
|--------|--------------|--------------|
| Ψ | 20 | $\mathbb{1}$ |
| χ | $\mathbb{1}$ | \square |

- ❖ This requires higher CUT scales
- ❖ Both axions are dynamical with a scale set by $SU(3)_{\text{diag}}$ confinement

(2) Introduce a second Δ to ensure PQ symmetry, then the resulting axion absorbs θ'

- ❖ Hybrid solution with a dynamical axion and a standard axion

Model II

Model II: Addition of a Second Scalar

- ❖ Instead of adding the massless χ , we include a second Δ field

$$\Delta \rightarrow \{\Delta_1, \Delta_2\}$$

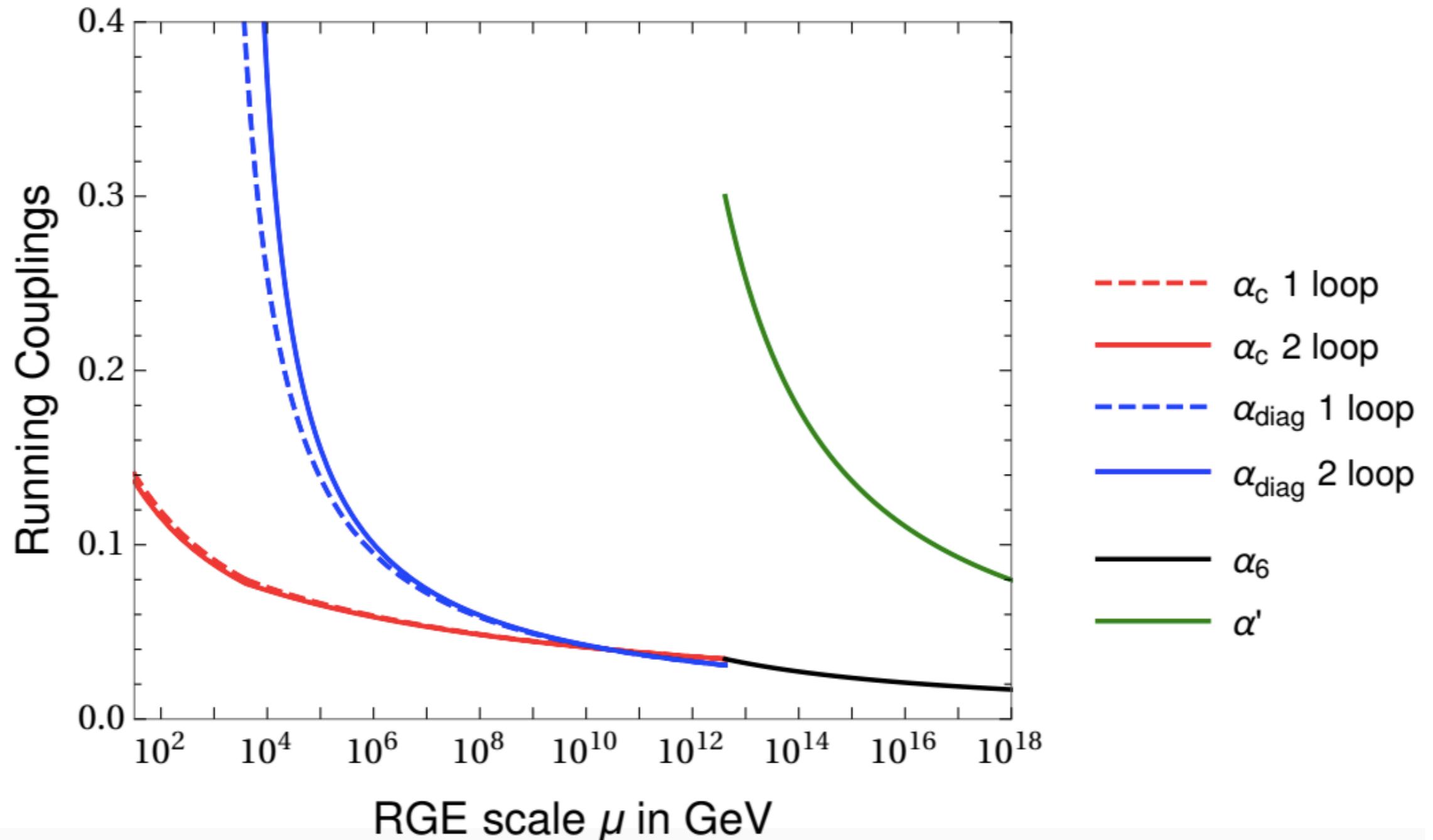
| | SU(6) | SU(3') | SU(2) _L | | | SU(3) | SU(3) _{diag} | SU(2) _L |
|--------|-------|--------|--------------------|--------------------------------------|-----------------|-------|-----------------------|--------------------|
| Ψ | 20 | 1 | 1 | $\xrightarrow{\Lambda_{\text{CUT}}}$ | 4 | □ | $\bar{\square}$ | 1 |
| χ | 1 | □ | 1 | | χ | 1 | □ | 1 |
| | | | | | 24 _ν | 1 | 1 | 1 |

$$PQ\{\Delta_1, \Delta_2, \overline{q'_R}, u'_L, d'_L\} = \{+1, -1, +1, +1, +1\}$$

- ❖ Note that the PQ symmetry forbids terms like:

$$y'_d d'_L \phi \overline{q'_R} \quad \& \quad y'_u u'_L \phi \overline{q'_R}$$

Model II: Unification and Confinement

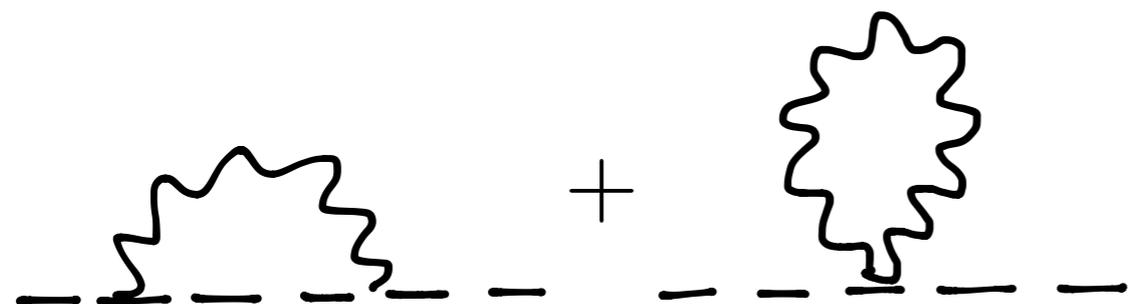


$SU(3)_{\text{diag}}$ Confinement

- ❖ The $U(3)$ flavor symmetry is broken by condensates: $\langle \bar{\psi}\psi \rangle$

$$U(3)_L \times U(3)_R \rightarrow U(3)_V$$

- ❖ This results in 9 pGB's $9 = 8_c + 1_c$
- ❖ Their masses get pushed up to the cutoff of the theory via interactions with gluons

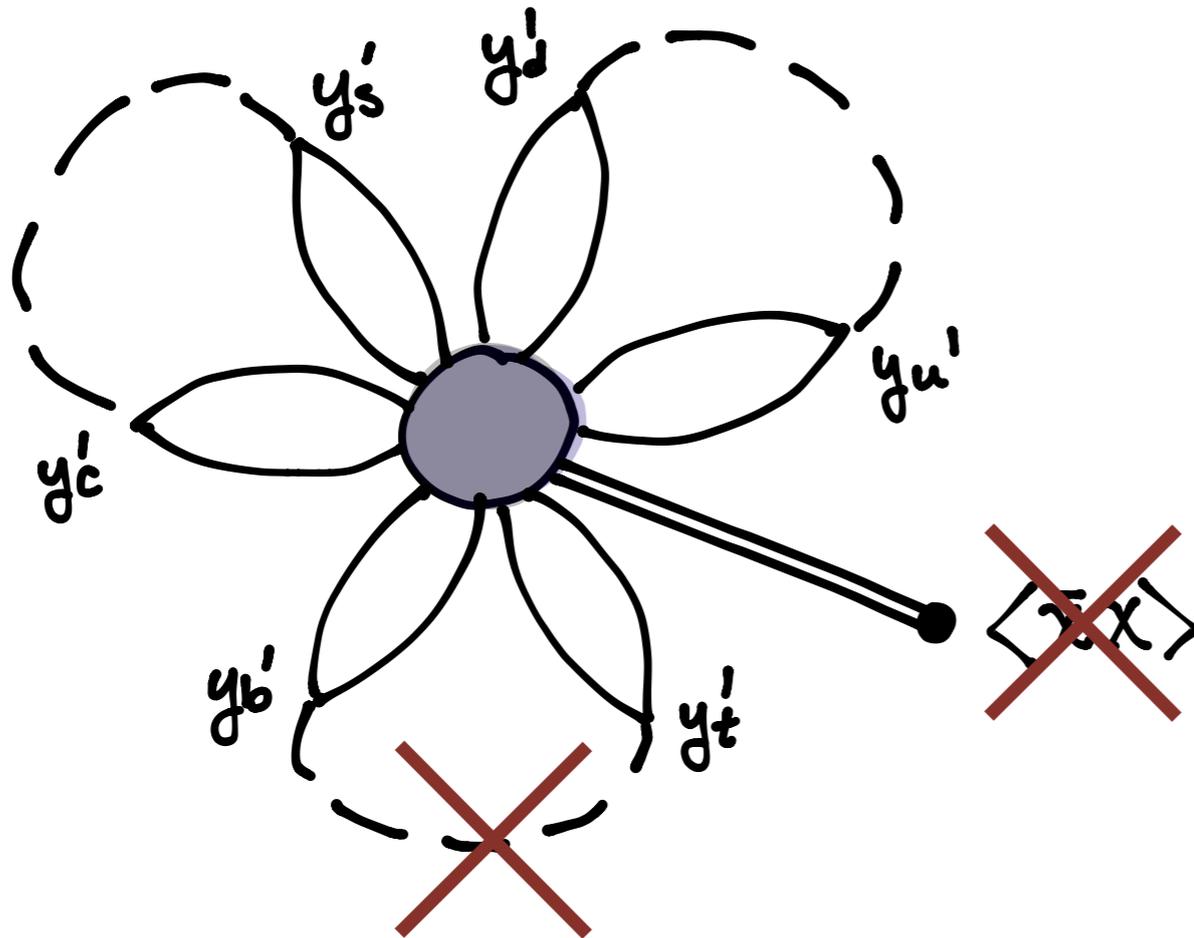


The diagram shows two Feynman diagrams for a quark self-energy correction. The first diagram is a quark line with a gluon loop (represented by a wavy line). The second diagram is a quark line with a ghost loop (represented by a dashed line). The diagrams are separated by a plus sign. An arrow points to the right, leading to the equation:

$$m^2(8_c) \approx \frac{9\alpha_c}{4\pi} \Lambda_{\text{diag}}^2$$

Model II: Small Size Instanton Contribution

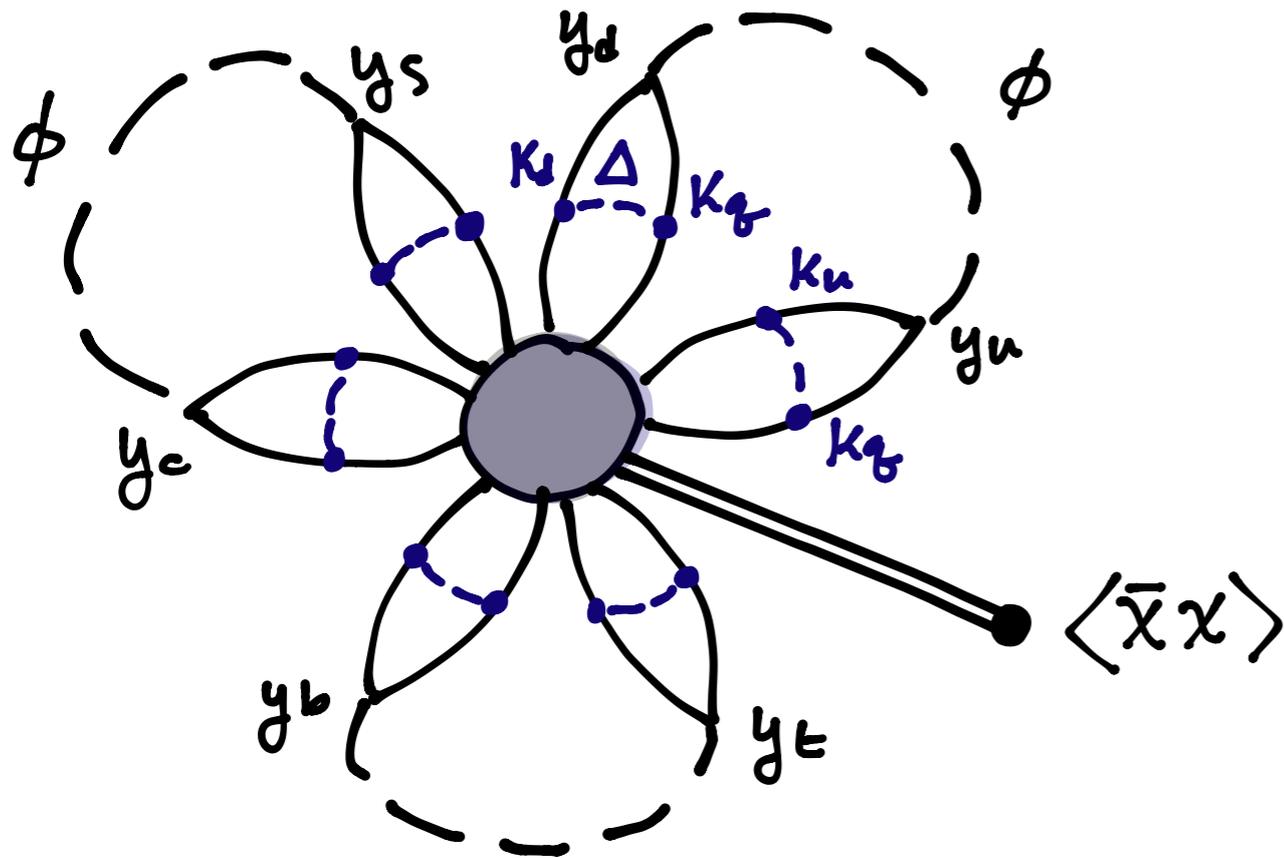
- ❖ Model I had the leading order contribution suppressed by:



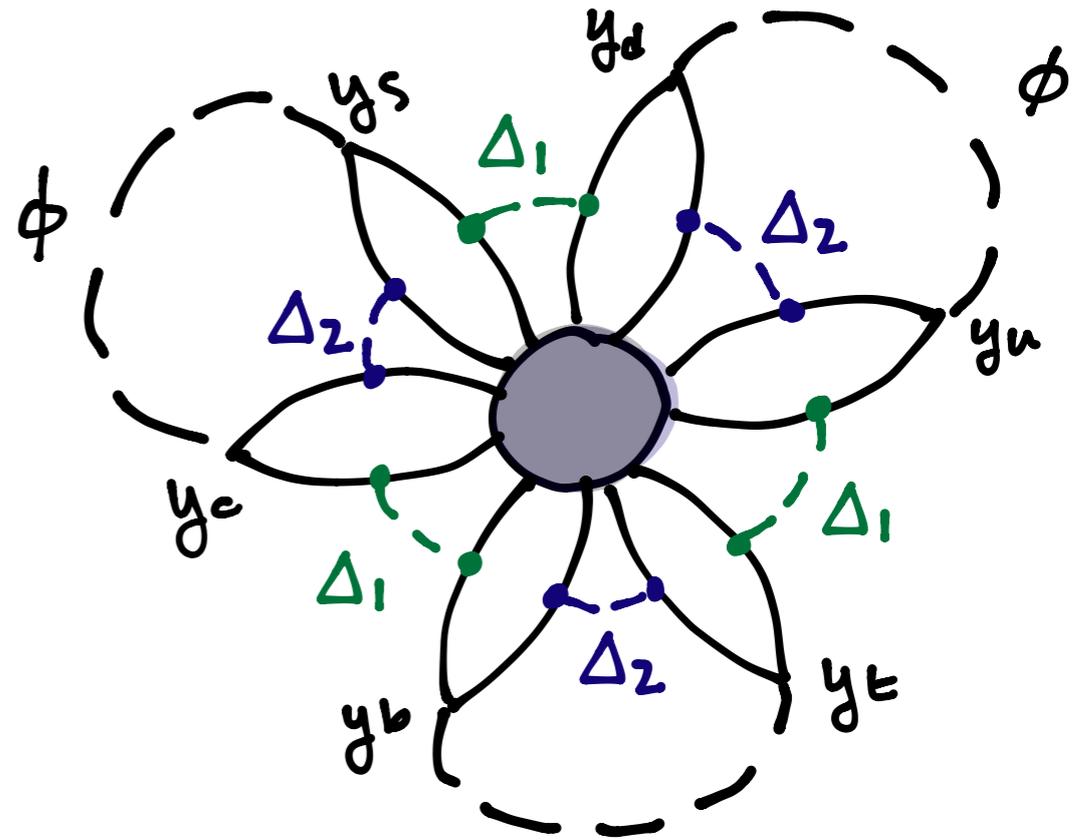
- ❖ No massless quarks charged under $SU(3)'$
- ❖ Prime Yukawa term is forbidden by the PQ symmetry

Model II: Small Size Instanton Contribution

- ❖ Model I had the subleading contribution suppressed by:

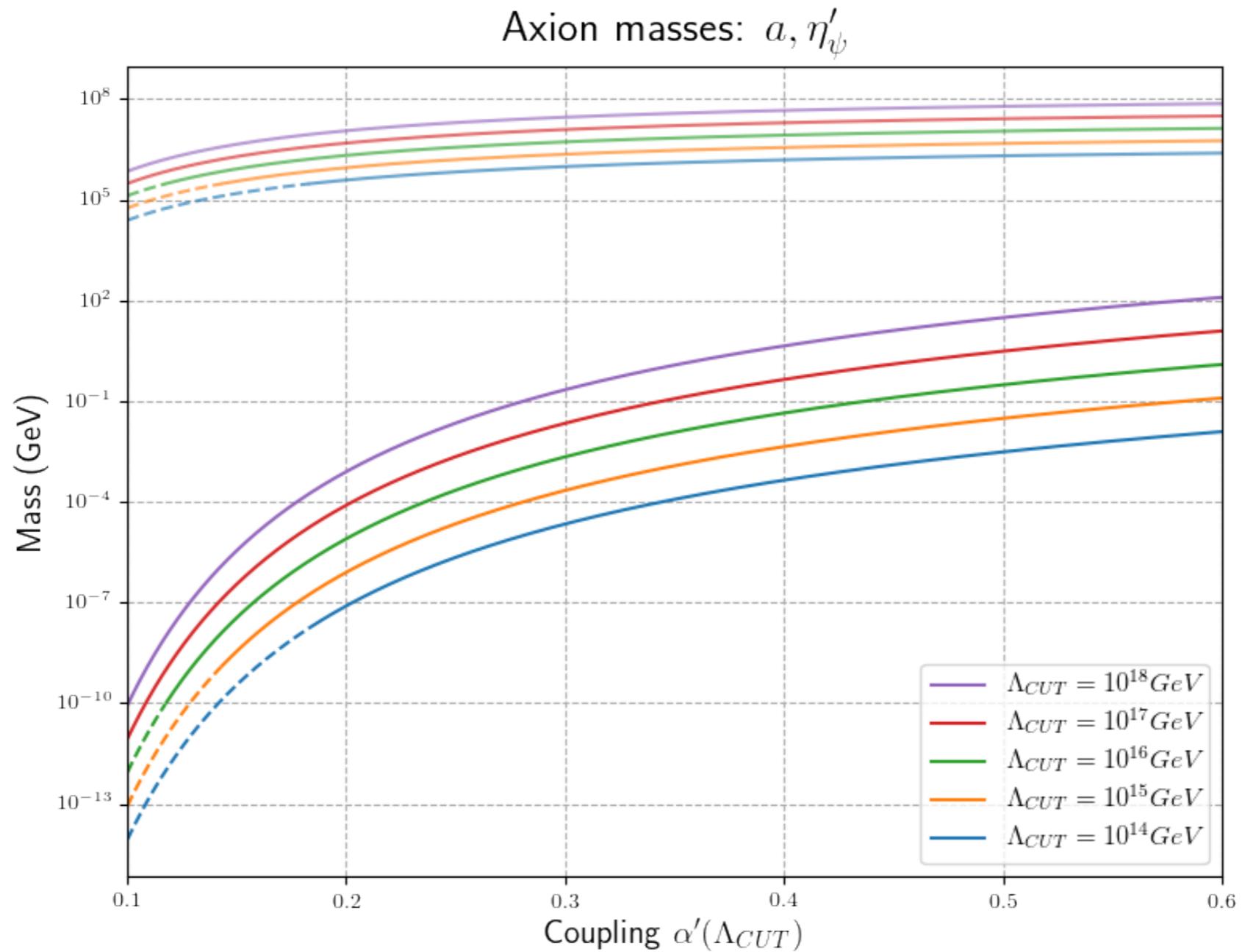


- ❖ Model II: the leading order contribution's suppression

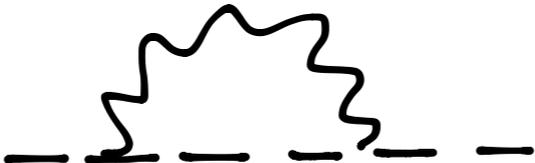
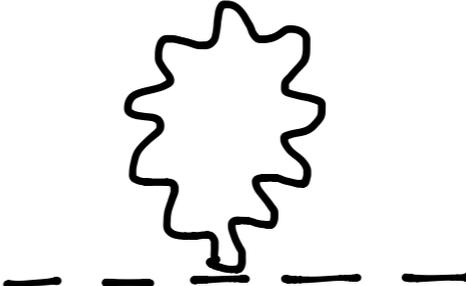


$$\Lambda_{SSI}^4 = - \int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \frac{1}{(4\pi)^{18}} \prod_i Y_{u_i}^{SM} Y_{d_i}^{SM} (\kappa_q^i)^2 \kappa_u^i \kappa_d^i$$

Axion masses



Low Energy Spectrum Summary

| | <u>Model 1</u> | <u>Model 2</u> |
|--|--|--|
| ❖ Axions | ❖ Generally too heavy to produce at colliders | ❖ One heavy, one light due to fermion suppression ❖ Couplings $\sim 1/\Lambda_{CUT}$ |
| ❖ Exotic QCD colored “pions” | ❖ Color octets ❖ Color triplets  | ❖ Color octets only  |
| ❖ Sterile neutrinos ψ_ν , suppressed by Λ_{CUT} , basically invisible | | |

Check in: Solution to the Strong CP Problem from the Low-E EFT

$$\mathcal{L}_{eff} = \Lambda_{SSI}^4 \cos\left(2\frac{\eta'_\chi}{f_d} - \bar{\theta}'\right) + \Lambda_{\text{diag}}^4 \cos\left(2\frac{\eta'_\chi}{f_d} + \sqrt{6}\frac{\eta'_\psi}{f_d} - \bar{\theta}' - \bar{\theta}_6\right) + \Lambda_{\text{QCD}}^4 \cos\left(\sqrt{6}\frac{\eta'_\psi}{f_d} - \bar{\theta}_6\right)$$

❖ The CP-Conserving minimum is

$$\left\langle \bar{\theta}' - 2\frac{\eta'_\chi}{f_d} \right\rangle = 0 \quad \left\langle \bar{\theta}_6 - \sqrt{6}\frac{\eta'_\psi}{f_d} \right\rangle = 0$$

❖ Rewriting with the axion fields expanded about their minima:

$$\mathcal{L}_{eff} = \Lambda_{SSI}^4 \cos\left(2\frac{\eta'_\chi}{f_d}\right) + \Lambda_{\text{diag}}^4 \cos\left(2\frac{\eta'_\chi}{f_d} + \sqrt{6}\frac{\eta'_\psi}{f_d}\right) + \Lambda_{\text{QCD}}^4 \cos\left(\sqrt{6}\frac{\eta'_\psi}{f_d}\right)$$

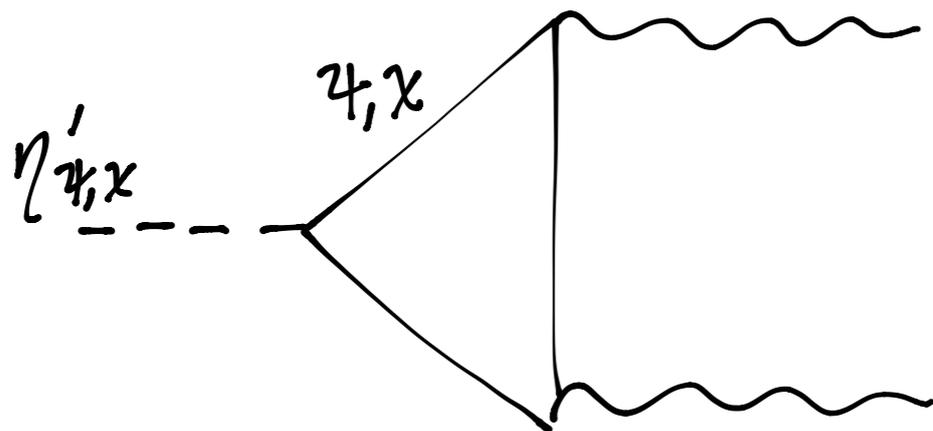
The η' Pseudoscalars

- ❖ The associated currents for the QCD singlets are:

$$j_{\psi_A}^\mu = \bar{\psi} \gamma^\mu \gamma^5 t^9 \psi \equiv f_d \partial^\mu \eta'_{\psi} \quad \diamond \quad t^9 = \frac{1}{\sqrt{6}} \mathbf{1}_{3 \times 3}$$

$$j_{\chi_A}^\mu = \bar{\chi} \gamma^\mu \gamma^5 \chi \equiv f_d \partial^\mu \eta'_{\chi} \quad \diamond \quad f_d \text{ is the pGB scale:}$$

$$\Lambda_{\text{diag}} \leq 4\pi f_d$$



$$\partial_\mu j_{\psi_A}^\mu = -\sqrt{6} \frac{\alpha_6}{8\pi} G_6 \tilde{G}_6$$

$$\partial_\mu j_{\chi_A}^\mu = -2 \frac{\alpha'}{8\pi} G' \tilde{G}'$$

The Dynamical Axions

- ❖ The dynamical axions above and below Λ_{CUT}

$$\mathcal{L} \ni -\frac{\alpha_6}{8\pi} \frac{\sqrt{6}\eta'_\psi}{f_d} G_6 \tilde{G}_6 - \frac{\alpha'}{8\pi} \frac{2\eta'_\chi}{f_d} G' \tilde{G}'$$

Λ_{CUT}



$$\mathcal{L} \ni -\frac{\alpha_c}{8\pi} \frac{\sqrt{6}\eta'_\psi}{f_d} G_c \tilde{G}_c - \frac{\alpha_{\text{diag}}}{8\pi} \left(\frac{2\eta'_\chi}{f_d} + \sqrt{6} \frac{\eta'_\psi}{f_d} \right) G_{\text{diag}} \tilde{G}_{\text{diag}}$$


- ❖ Note that the axion scale here is f_d and not Λ_{CUT}

The Pseudoscalar Mass Matrix

The $SU(3)'$
instanton
contribution

The $SU(3)_{\text{diag}}$
instanton
contribution

$$M_{\eta'_\chi, \eta'_\psi, \eta'_{\text{QCD}}}^2 = \begin{pmatrix} 4 \frac{(\Lambda_{SSI}^4 + \Lambda_{\text{diag}}^4)}{f_d^2} & 2\sqrt{6} \frac{\Lambda_{\text{diag}}^4}{f_d^2} & 0 \\ 2\sqrt{6} \frac{\Lambda_{\text{diag}}^4}{f_d^2} & 6 \frac{(\Lambda_{\text{diag}}^4 + \Lambda_{\text{QCD}}^4)}{f_d^2} & 2\sqrt{6} \frac{\Lambda_{\text{QCD}}^4}{f_\pi f_d} \\ 0 & 2\sqrt{6} \frac{\Lambda_{\text{QCD}}^4}{f_\pi f_d} & 4 \frac{\Lambda_{\text{QCD}}^4}{f_\pi^2} \end{pmatrix}$$

$$\Lambda_{SSI} \lesssim 10^4 \text{ TeV}$$

$$\Lambda_{\text{diag}} \sim \text{few TeV}$$

Model II: Addition of a Second Scalar and Explicit Lagrangian

- ❖ Instead of adding the massless χ , we include a second Δ field

$$\Delta \rightarrow \{\Delta_1, \Delta_2\}$$

- ❖ Using both scalars, we can give the $SU(6) \times SU(3)'$ theory a PQ symmetry

$$\mathcal{L} \ni \kappa_q \overline{q'_R} \Delta_1^* Q_L + \kappa_u u'_L \Delta_2 \overline{U_R} + \kappa_d d'_L \Delta_2 \overline{D_R} + \text{h.c.}$$

$$PQ\{\Delta_1, \Delta_2, \overline{q'_R}, u'_L, d'_L\} = \{+1, -1, +1, +1, +1\}$$

Thank you!